An Overview of Non-Stationary Property for Massive MIMO Channel Modeling

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Abstract

Massive multiple-input multiple-output (MIMO) emerges as one of the most promising technologies for 5G mobile communication systems. Compared to the conventional MIMO channel models, channel researches and measurements show that significant non-stationary properties rise in massive MIMO channels. Therefore, an accurate channel model is indispensable for the sake of massive MIMO system design and performance evaluation. This article presents an overview of methods of modeling non-stationary properties on both the array and time axes, which are mainly divided into two major categories: birth-death (BD) process and cluster visibility region (VR) method. The main concepts and theories are described, together with useful implementation guidelines. In conclusion, a comparison between these two methods is made.

Keywords

birth-death process; cluster visibility region method; massive MIMO channel model; non-stationary properties

1 Introduction

Massive multiple-input multiple-output (MIMO) systems, which are equipped with tens or even hundreds of antennas, have been proposed to meet the increasing traffic demand of the future wireless communication systems. Compared to conventional MIMO systems, massive MIMO systems are able to substantially improve capacity, link reliability, energy efficiency and spectral efficiency [1]−[4]. For the sake of MIMO system design and performance evaluation, it is indispensable to develop accurate and efficient small-scale fading channel models. Generally, there are three generic approaches for conventional MIMO channel modeling, namely the stochastic model, deterministic-based model and geometry-based stochastic model (GBSM). The GBSM has been widely used as an efficient method to simulate the wireless propagation channels, because it generates the location of scatterers according to a certain probability distribution rather than specific channel environment. So far, many standardized GBSMs are proposed [5]−[7]. However, according to the channel measurements [8], [9], new characteristics of the massive systems make the conventional MIMO channel models not be effective to be applied in massive MI-

MO channels directly.

Non - stationary property is one of the new characteristics that makes massive MIMO channels different from conventional ones. Non - stationary property generally includes two aspects: angle of arrival (AOA) shifts at the receiver side and dynamic properties of clusters on both the array and time axes. AOA shifts can be described completely through spherical wave - front assumption according to geometrical relationships among transmitter, receiver and clusters [10]. This article does not focus on this aspect. Dynamic properties of clusters on both the array and time axes generally refer to the facts that each antenna at different physical location has different cluster sets and the location of cluster is changing over time. This property is mainly described through birth-death (BD) process and cluster visibility region (VR) method.

The BD process was first investigated to model the non-stationary properties of clusters on the time axis only [11]−[14]. After this property was observed on the large antenna array [8], [9], i.e., appearance and disappearance of clusters can occur on the array axis, the BD process was extended to the antenna array [15]−[17]. The authors in [15] proposed a 2D ellipse model that describes wide-band massive MIMO channels by many con - focal ellipses. Similarly, a 2D multi - ring channel model with the same center for massive MIMO was proposed in [16]. For both of them, the geometrical relationships related to the delays of multi-path components (MPCs) are assumed to mimic the distribution of clusters. In [17], a 3D twin - cluster model

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was proposed, where a cluster was divided into two representations of itself (one at the transmitter and the other at the receiver). Then the complicated scattering environment was abstracted by a virtual link between the two representations of this cluster. Although the descriptions of geometrical relationships are different in these modeling approaches, the methods of modeling non-stationary properties of clusters on both the array and time axes are all based on the BD process.

The cluster VR method models the non-stationary properties of clusters from the cluster perspective. VR is typically assigned to the cluster in such a way that when an terminal enters a VR, the cluster assigned to this VR is active (contributes to the impulse response). The cluster VR method was investigated on the time axis at first [18], and after the non-stationary properties of clusters on the large antenna array in massive MIMO was observed, it was extended [19]–[21]. In [19], a 3D two-cylinder regular-shaped GBSM for non-isotropic scattering massive MIMO channels was proposed. Non-stationary properties of clusters on the array axis were described by using a virtual sphere. In [20] and [21], the concept of VR in COST 2100 channel model was extended. In [20], the cluster VR was divided into two categories: the observed VR and the true VR. The cumulative distribution function (CDF) of the observed VR size could be written as a function of the probability density function (PDF) of the true VR size. On the other hand, the distribution of the true VR lengths could be obtained based on measurements. In [21], cluster VR on the array axis was characterized by the partially visible clusters and wholly visible clusters. Therefore, when using the cluster VR method to describe non-stationary properties of clusters, the definition of VR is most important.

This article aims to give a concise overview of methods of modeling non-stationary properties of clusters for massive MIMO, which mainly include two categories: BD process and cluster VR method. For the BD process, because of uniform modeling approach, a main flow chart that describes non-stationary properties of clusters on both the array and time axes is given. For the cluster VR method, some typical representatives of defining VR in different modeling approach are reviewed. A brief comparison of these two different methods is also given.

2 Birth-Death Process

The BD process is widely investigated to describe non-stationary properties of clusters on both the array and time axes in massive MIMO channel model. In this process, cluster evolution along array and time axes are calculated separately. The main flow of BD process is presented below.

Let N_{total} be the total number of clusters that are observable to at least one transmit antenna and one receive antenna. The value of N_{total} can be expressed as

$$N_{total} = \text{card}(\bigcup_{l=1}^{M_T} \bigcup_{k=1}^{M_R} (C_l^T(t) \cap C_k^R(t))), \tag{1}$$

where the operator card$(\cdot)$ denotes the cardinality of a set, M_T and M_R denote the number of antenna elements at the transmitter and receiver, respectively, and $C_l^T(t)(C_k^R(t))$ denotes the cluster set in which clusters are observable to the l-th transmit antenna (the k-th receive antenna) at time instant t. Then, a cluster is observable to the l-th transmit antenna and the k-th receive antenna if and only if this cluster is in the set $\{C_l^T(t) \cap C_k^R(t)\}$. Cluster evolution on both the array and time axes determine cluster sets in $C_l^T(t)$ and $C_k^R(t)$.

Cluster evolution on the array axis is operated first. We assume the initial number of clusters N and the initial cluster sets of the 1-st transmit and receive antenna $C_1^T = \{c_x^T : x = 1, 2, ..., N\}$ and $C_1^R = \{c_x^R : x = 1, 2, ..., N\}$ at the initial time instant t are given, where c_x^T and c_x^R are two representations of Cluster$_x$, the subscript x represents the x-th cluster in cluster sets. Then, these clusters in cluster sets C_1^T and C_1^R evolve according to BD process on the array axis to recursively generate the cluster sets of the rest of antennas at the transmitter and receiver at the initial time instant t, which can be expressed as

$$
\begin{aligned}
C_{l-1}^T(t) \xrightarrow{E} C_l^T(t) \quad (l = 2, 3, ..., M_T) \\
C_{k-1}^R(t) \xrightarrow{E} C_k^R(t) \quad (k = 2, 3, ..., M_R)
\end{aligned}, \tag{2}
$$

where the operator $\xrightarrow{E}$ denotes cluster evolution on either the antenna array or time axes. The survival probabilities of the clusters inside the cluster sets on the array axis at the transmitter $P_{survival}^T$ and at the receiver $P_{survival}^R$ can be calculated as

$$
\begin{aligned}
P_{survival}^T = e^{-\lambda_R \frac{\delta_T}{D_c^a}} \\
P_{survival}^R = e^{-\lambda_R \frac{\delta_R}{D_c^a}}
\end{aligned}, \tag{3}
$$

where D_c^a is the scenario-dependent correlation factor on the array axis, λ_G (per meter) and λ_R (per meter) denote the cluster generation rate and the recombination rate respectively, and δ_T and δ_R are antenna spacing of transmit and antenna array respectively. According to the BD process, the average number of newly generated clusters N_{new}^T and N_{new}^R on the array axis can be calculated as

$$
\begin{aligned}
E[N_{new}^T] = \frac{\lambda_G}{\lambda_R}(1 - e^{-\frac{\delta_T}{D_c^a}}) \\
E[N_{new}^R] = \frac{\lambda_G}{\lambda_R}(1 - e^{-\frac{\delta_R}{D_c^a}})
\end{aligned}, \tag{4}
$$

where $E[\cdot]$ denotes the expectation. Based on the BD process, clusters evolve gradually on the antenna array. To put it another way, some initial clusters may disappear for certain antennas, and some new clusters may appear. An example of cluster evolution on the receive antenna array is shown in **Fig. 1** [15]. It can be seen that these clusters evolve gradually from twenty clusters that are observable to the first antenna element originally. Four clusters of original twenty clusters disappear, name-

ly cluster₁₀, cluster₁₄, cluster₁₅ and cluster₂₀. Meanwhile, five new clusters appear. As a result, different antenna elements may observe different cluster sets, like receive antennas C_4^R and C_{31}^R.

At the next time instant $t = t_{m+1}$, cluster evolution on the time axis is operated as
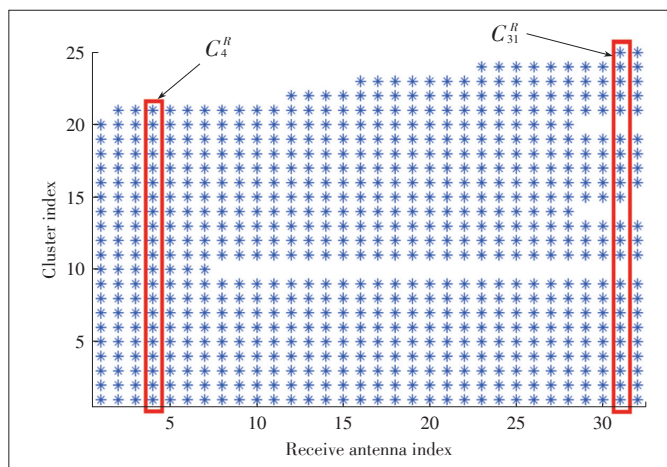
$$
\begin{aligned}
C_l^T(t_m) &\xrightarrow{E} C_l^T(t_{m+1}) \\
C_k^R(t_m) &\xrightarrow{E} C_k^R(t_{m+1})
\end{aligned}.
\tag{5}
$$

According to [22], to reproduce the evolution on the time axis, the channel fluctuation, which stands for a measure of variation of scattering environment in time domain, should be defined as q_{m+1} at $t = t_{m+1}$. q_{m+1} consists of two parts, namely the fluctuation caused by the movement of receiver and the fluctuation movement of clusters. Given the scenario-dependent correlation factor D_c^s, each cluster survives with probability $P_{survival}$ and mean number of newly generated clusters $E[N_{new}(t_{m+1})]$ can be presented as

$$
P_{survival}(q_{m+1}) = e^{-\frac{\lambda_R q_{m+1}}{D_c^t}},
\tag{6}
$$

$$
E[N_{new}(t_{m+1})] = \frac{\lambda_G}{\lambda_R}(1 - e^{-\frac{\lambda_R q_{m+1}}{D_c^a}}).
\tag{7}
$$

After cluster evolution on the time axis, as (5)−(7) show, all clusters can be categorized as survived clusters or newly generated clusters. For the survived cluster, channel parameters should be updated from t_m to t_{m+1} according to the geometrical relationships. For the newly generated cluster, it is first attached to one transmit antenna element randomly, and then evolves along transmit antenna array to determine whether it can be observed based on the survival probabilities $P_{survival}^T$ on the array axis. The same judge process applies to the receive antenna array too. Finally, the cluster is added to antenna cluster sets if and only if it survives at both the transmitter and re-
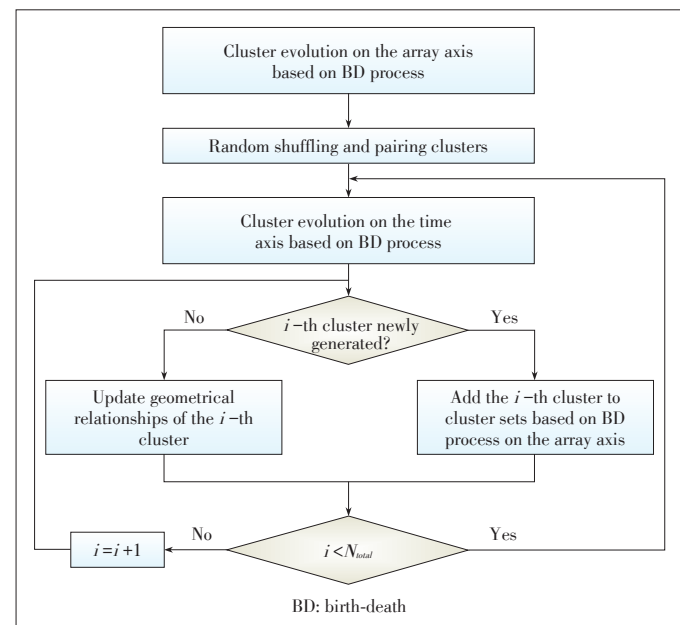
ceiver side. The main flow of cluster evolution on both array and time axes based on the BD process is given in **Fig. 2**.

3 Cluster Visibility Region Method

The cluster VR method describes non-stationary properties of clusters on both the array and time axes from the cluster perspective. In the exsiting channel models, different definitions of VR determine the methods of modeling cluster evolution. Therefore, the descriptions of VR in some representative channel models are reviewed separately.
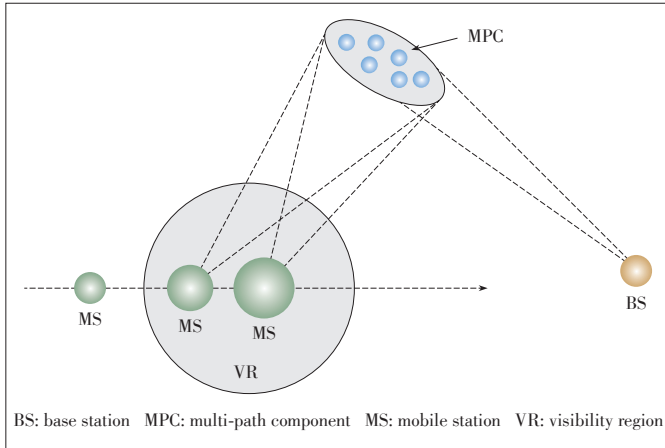
3.1 COST 2100 Channel Model

In the COST2100 channel model, the cluster VR method is used to describe cluster evolution on the time axis. Specifically, clusters are divided into three categories: local clusters, single-bounce clusters and multiple-bounce clusters. VR confines the cluster activity within a limited geographical area. A cluster is depicted as an ellipsoid as viewed from mobile stations (MS) and from base stations (BS), and the size of the circle around the MS represents the visibility level of the cluster to the BS-MS channel, as illustrated in **Fig. 3**. After the MS moves into the VR, it receives signals scattered by the related cluster. As it moves towards the VR center, the cluster smoothly increases its visibility. The visibility is accounted mathematically by a VR gain, which grows form 0 to 1 upon entrance of the VR. By employing the VR size and the VR gain, cluster evolution at the receiver side can be described in the COST2100 channel model. Eventually, the channel impulse response (CIR) is obtained by the superposition of the MPCs from all active clusters determined by the position of the termi-

▲Figure 1. An example of cluster evolution on the receive antenna array [15].

▲Figure 2. The main flowchart of cluster evolution on both the array and time axes.

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▲Figure 3. VR concept.

BS: base station   MPC: multi-path component   MS: mobile station   VR: visibility region

nal. Additionally, parameterization and validation of the COST2100 channel model are given in [23] and [24] based on measurements.

3.2 3D Two-Cylinder Channel Model

The 3D two-cylinder channel model extends the concept of VR to the antenna array. All the scatterers are distributed on the surface of a cylinder as equivalent, and each antenna has its own visible area of scatterers by using a virtual sphere, where the radius is r and the center is the antenna element itself. In this case, scatterers on the surface of the cylinder can be seen by an antenna element only if the distance between them is less than r, as shown in **Fig. 4**. The radius r of the virtual sphere can be calculated according to the distance between two antenna elements and the correlation of their channel impulse responses. Furthermore, channel impulse responses are affected by the distribution of scatterers. If the distance is $\lambda/2$, correlation coefficient is 0.9, and scatterers are uniformly distributed on the surface of the cylinder, whose radius is R, the r can be expressed in terms of R as

$$r < R \times 2.7856 . \tag{8}$$

3.3 Channel Model Based on Extended Concepts of VR

The channel models proposed in [20] and [21] extend the concept of VR in COST2100 channel model to the antenna array. We take the extension in [20] as an example. In [20], VR size and visibility gain are discussed based on measurements. As shown in **Fig. 5**, the VR size of some clusters is entirely inside the array, while that of other clusters overlaps one or both ends of the antenna array. For the former case, the observed size of VR on the antenna array is the cluster's true VR size, while for the latter case, the true VR size may be much larger than what is observed on the antenna array.

As a result, VR size should be described in two stages. First, the relationship between the observed VR size and the true VR size is determined, as illustrated in **Fig. 6**. The CDF

of the observed VR size $K_\Delta(y)$ can be written as a function of PDF of the true VR size $f_\alpha(\nu)$, and it can be expressed as

$$K_\Delta(y) = \begin{cases} K'_\Delta(y), & y \leqslant L \\ 1, & y > L \end{cases}, \tag{9}$$

$$K'_\Delta(y) = \int_{\Delta_0}^{y} f_\alpha(\nu)d\nu + 2y\int_y^\infty \frac{1}{L+\nu}f_\alpha(\nu)d\nu - 2\Delta_0\int_{\Delta_0}^\infty \frac{1}{L+\nu}f_\alpha(\nu)d\nu, \tag{10}$$

where L is the length of the array, and Δ_0 is the smallest observation of the VR size on the array due to measurement data processing. Second, the particular distribution of the true VR
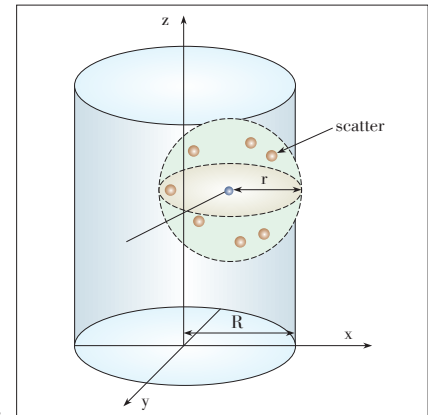

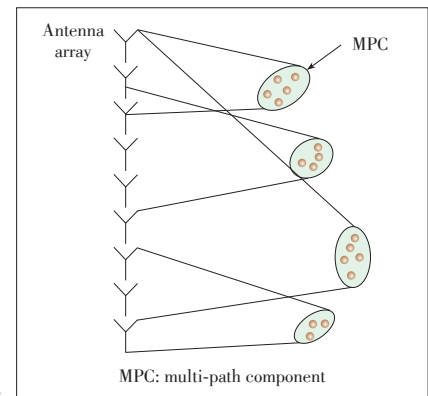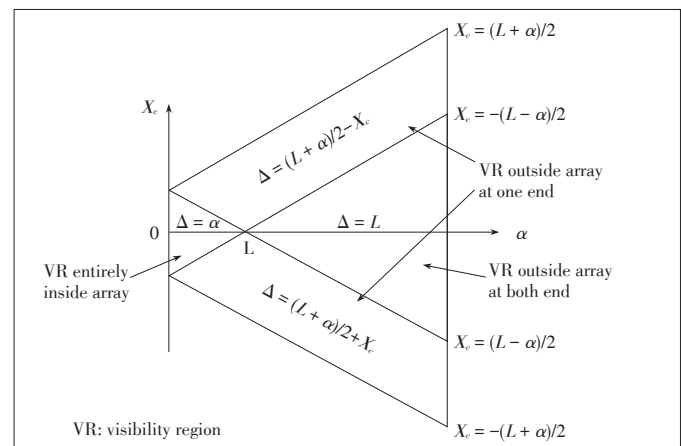Figure 4.▶
VR of the antenna array.

Figure 5.▶
Extension of the concept of VR to the antenna array.

MPC: multi-path component

▲Figure 6. Relationship between a cluster's true VR size and observed VR size on the array Δ, depending on the array center position X_c.

size is calculated through the maximum likelihood estimate (MLE) approach based on the measurements. Finally, the VR size can be calculated.

4 Conclusions

In this article, we review methods of modeling non‐stationary properties of clusters on both the array and time axes, namely BD process and cluster VR method. The main flow of BD process is given, and different definitions of VR in some representative channel models are reviewed. Based on mathematical derivation, the theory of BD process is more mature and complete, and its accuracy has been proved by lots of researches. However, it is too complex and lacks of intuitive geometric characteristics between clusters and the antenna array. On the other hand, the cluster VR method pays more attention to geometrical distribution of clusters, which makes it more natural to be integrated into the channel model based on stochastic geometry. However, further study is necessary to obtain the complete information of VR. From our point of view, a better scheme of modeling cluster evolution is to combine these two methods together. This scheme can reduce the complexity of modeling, and also reflect the geometrical characteristics of the channel.

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