ON A SPHERE OF INFLUENCE GRAPH IN A ONE-DIMENSIONAL SPACE

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Abstract

A sphere of influence graph generated by a finite population of generated points on the real line by a Poisson process is considered. We determine the expected number and variance of societies formed by population of $n$ points in a one-dimensional space.

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1. Introduction

Let $X = \{X_1, X_2, \ldots, X_n\}$ be the set of $n$ points of $R^d$ chosen randomly and independently with the same probability. Let

$$r(X_i) = \min_{X_j \in X \setminus \{X_i\}} d(X_i, X_j)$$

denote the minimum distance between $X_i$ and any other point in $X$. The open ball

$$B_i = \left\{ X \in R^d : d(X_i, X) < r_i \right\}$$

with center $X_i$ and radius $r_i$ is the sphere of influence graph at $X_i$ ($i = 1, \ldots, n$). The random sphere of influence graph $SIG(X)$ has vertex set $X$ with edges corresponding to pairs of intersecting spheres of influence.
In other words two vertices, say $X_i$ and $X_j$, are connected by an edge if and only if

$$r(X_i) + r(X_j) > d(X_i, X_j).$$

The definition of the sphere of influence graph was introduced in [10] by Touissant. These graphs have been widely investigated recently. It is known that on the Euclidean plane the sphere of influence graph always has a vertex of degree at most 18 (see [5], for related results see [1, 7]). Füredi [4] showed that the expected number of edges $E(n, \mathcal{N})$ of the random sphere of influence graph on $n$ vertices in normed space $\mathcal{N}$ is equal to

$$E(n, \mathcal{N}) = C(d)n + o(n),$$

where $C(d)$ is a constant depending only on the dimension of the space and

$$\frac{\pi}{8}2^d < C(d) < \left(1 + \frac{1}{2d}\right)\frac{\pi}{8}2^d.$$

This result was also proved independently by Chalker et al in [2]. In [6] Hitczenko, Janson and Yukich proved analogue result for variance. They showed

$$c(d)n \leq Var(n, \mathcal{N}) \leq C(d)n,$$

where constants $c(d)$ and $C(d)$ depend only of the space dimension.

Consider a population of $n$ points generated by some random process in $\mathbb{R}^d$ and its resulting sphere of influence graph. We thereby generate clusters of points that are connected by edges. We call these clusters societies. The following questions arise:

- Let $M$ denote the number of societies formed. What is the distribution of $M$?
- Let $N$ denote the size of society, i.e., the number of individuals (points) in a society. What is the distribution of $N$?
- Form the convex hull of each society. What is
  - the content (area, volume) covered by a society?
  - the fraction of $\mathbb{R}^d$ that is contained in some society, as $n \to \infty$?

In this paper our main concern is with the random variable $M$. 
2. One-Dimensional Societies

Let the population consist of \( n \) points, \( X_i, 1 \leq i \leq n \), generated on the real line by a Poisson process. Let \( X_{(i)} \) denote the corresponding order statistics and let

\[
A_i = X_{(i+1)} - X_{(i)}, \quad 1 \leq i \leq n - 1,
\]

denote the lengths of the spacings between adjacent points. Societies are determined by the relative magnitudes of the spacings. The \( A_i \) are identically distributed. Moreover, the distribution of the vector of ranks of the \( A_i \) is discrete uniform.

Consider now the number of societies \( M \) formed by a population of \( n \) points. Clearly, \( M \) satisfies \( 1 \leq M \leq \lfloor \frac{n}{2} \rfloor \). For fixed \( n \), let

\[
P_n(M = m) = P_n(m)
\]

denote the distribution of \( M \). Obviously, \( P_2(1) = P_3(1) = 1 \).

The following technical lemma will be helpful in the proof of the main theorem.

**Lemma 1.** Let \( 2 \leq m \leq \lfloor \frac{n}{2} \rfloor \). If for \( n \geq 4 \)

\[
P_n(m) = \sum_{i=2}^{n-2} \frac{1}{4} P_i(1) P_{n-i}(m - 1)
\]

and for \( n \geq 2 \)

\[
P_n(1) = (n - 1)2^{2-n}
\]

then

\[
P_n(m) = 2^{2-n} \binom{n-1}{2m-1}
\]

for \( n \geq 2 \).

**Proof.** Let \( m = 2 \). Then

\[
P_n(2) = \sum_{i=2}^{n-2} \frac{1}{4} P_i(1) P_{n-i}(1) = \sum_{i=2}^{n-2} \frac{1}{4} 2^{2-i}(i - 1)2^{2-n+i}(n - i - 1)
\]

\[
= 2^{2-n} \sum_{i=1}^{n-3} i(n - i - 2) = 2^{2-n} \binom{n-1}{3}.
\]
Assume that lemma is true for \( m \leq j \) and let \( m = j + 1 \). Then by induction

\[
P_n(j + 1) = \sum_{i=2}^{n-2} \frac{1}{4} P_i(1) P_{n-i}(j) = \sum_{i=2}^{n-2} \frac{1}{4} 2^{2-i} (i-1) 2^{2-n+i} \left( \frac{n-i-1}{2j-1} \right)
\]

\[
= 2^{2-n} \sum_{i=1}^{n-3} i \left( \frac{n-i-2}{2j-1} \right) = 2^{2-n} \left( \frac{n-1}{2j+1} \right)
\]

which completes the proof. □

**Theorem 2.** Let \( E_n(M) \) and \( Var_n(M) \) denote the mean and the variance of the number of societies formed in a population of \( n \) individuals. Then

\[
E_n(M) = \begin{cases} 
2 & \text{for } n = 2, \\
\frac{n+1}{4} & \text{for } n \geq 3,
\end{cases}
\]

and

\[
Var_n(M) = \begin{cases} 
0 & \text{for } n = 2, 3, \\
\frac{n-1}{16} & \text{for } n \geq 4.
\end{cases}
\]

**Proof.** Let us assume that \( A_{n-1} \geq A_{n-2} \). Then independently from the value of \( A_{n-3} \), vertices \( X_{(n-1)} \) and \( X_{(n-2)} \) are connected by an edge. So by the above assumption the number of societies formed by population of \( n \) points is equal to one with probability

\[
\frac{1}{2} P_{n-1}(1).
\]

Now, let \( A_{n-1} < A_{n-2} \). In this case the existence of only one society formed by \( n \) points, under condition that first \( n-2 \) points formed one society, depends on lengths \( A_{n-3}, A_{n-2}, A_{n-1} \). Notice that two vertices \( X_{(n-1)} \) and \( X_{(n-2)} \) are not connected by an edge if the following inequality holds

\[
A_{n-1} + A_{n-3} < A_{n-2}.
\]

Assume that \( A_{n-3} + A_{n-2} + A_{n-1} = l \). Then the probability of the event

\[
A_{n-2} > \frac{l}{2},
\]
i.e., probability that vertices $X_{(n-1)}$ and $X_{(n-2)}$ are not connected by an edge, is equal to

$$P\left(A_{n-2} > \frac{1}{2}\right) = \frac{\frac{1}{2}l^2}{\frac{1}{2}l^2} = \frac{1}{4}. $$

Thus we obtain that if $A_{n-1} < A_{n-2}$, the number of societies formed by population of $n$ points is equal to one with probability

$$\frac{1}{2}P_{n-1}(1) - \frac{1}{4}P_{n-2}(1).$$

Consequently population of $n$ individuals forms one society with the probability

$$P_{n}(1) = P_{n-1}(1) - \frac{1}{4}P_{n-2}(1).$$

Solving this recurrence equation and considering boundary conditions we obtain

\[ (*) \quad P_{n}(1) = (n - 1)2^{2-n}, \quad n \geq 2. \]

Let $B_i$ denote the event that two vertices, say $X_{(i)}$ and $X_{(i+1)}$, are the first ones that are not connected by an edge in the sphere of influence graph. It means that the number of societies formed by population of first $i$ vertices is equal to one, while population of first $i + 2$ vertices form two societies and the number of societies formed by population of last $n - i$ points is equal to $m - 1$, assuming that $M = m$. Then

$$P_{n}(M = m|B_i) = P_{n-i}(M = m - 1).$$

Therefore for $n \geq 4$

$$P_{n}(M = m) = \sum_{i=2}^{n-2} P_{n}(m|B_i)P(B_i)$$

$$= \sum_{i=2}^{n-2} \frac{1}{4}P_{i}(1)P_{n-i}(m - 1).$$

This and $(*$) imply (see Lemma 1) that

$$P_{n}(m) = 2^{2-n}\binom{n-1}{2m-1}$$

for $1 \leq m \leq \lfloor \frac{n}{2} \rfloor$. 
Now we can calculate the expected value of number of societies formed by \( n \) points. For \( n \geq 3 \) we have

\[
E_n(M) = \sum_{i=1}^{\lfloor \frac{n}{2} \rfloor} i P_n(i) = \sum_{i=1}^{\lfloor \frac{n}{2} \rfloor} 2^{2-n} \binom{n-1}{2i-1} i
\]

\[
= 2^{1-n} \sum_{i=1}^{\lfloor \frac{n}{2} \rfloor} \left( \frac{n-1}{2i-1} \right) 2i = 2^{1-n} \left( 2^{n-2} + (n-1)2^{n-3} \right)
\]

\[
= \frac{n+1}{4}.
\]

Consequently

\[
E_n(M) = \begin{cases} 
2 & \text{for } n = 2, \\
\frac{n+1}{4} & \text{for } n \geq 3.
\end{cases}
\]

The second moment (for \( n \geq 4 \)) is equal to

\[
E_n(M^2) = \sum_{i=1}^{\lfloor \frac{n}{2} \rfloor} i^2 P_n(i) = \sum_{i=1}^{\lfloor \frac{n}{2} \rfloor} 2^{2-n} \binom{n-1}{2i-1} i^2
\]

\[
= 2^{-n} \sum_{i=1}^{\lfloor \frac{n}{2} \rfloor} \left( \frac{n-1}{2i-1} \right) (2i)^2
\]

\[
= 2^{-n} \left( n2^{n-2} + (n-1)2^{n-3} + (n-1)(n-2)2^{n-4} \right)
\]

\[
= \frac{n(n+3)}{16}.
\]

And thus we obtain

\[
Var_n(M) = \begin{cases} 
0 & \text{for } n = 2, 3, \\
\frac{n-1}{16} & \text{for } n \geq 4.
\end{cases}
\]

Although we formulated the problem for \( \mathbb{R}^d \), we provided results only for the one-dimensional case. Even for simpler model of nearest neighbour graph (see [11] and [3]), higher-dimensional situations become complex enough to require simulation.
References


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