

FIRST-PASSAGE PERCOLATION ON RANDOM GEOMETRIC GRAPHS AND AN APPLICATION TO SHORTEST-PATH TREES

C. HIRSCH,* *Ulm University*

D. NEUHÄUSER,* *Ulm University*

C. GLOAGUEN,** *Orange Labs*

V. SCHMIDT,* *Ulm University*

Abstract

We consider Euclidean first-passage percolation on a large family of connected random geometric graphs in the d -dimensional Euclidean space encompassing various well-known models from stochastic geometry. In particular, we establish a strong linear growth property for shortest-path lengths on random geometric graphs which are generated by point processes. We consider the event that the growth of shortest-path lengths between two (end-) points of the path does not admit a linear upper bound. Our linear growth property implies that the probability of this event tends to zero sub-exponentially fast if the direct (Euclidean) distance between the endpoints tends to infinity. Besides, for a wide class of stationary and isotropic random geometric graphs, our linear growth property implies a shape theorem for the Euclidean first-passage model defined by such random geometric graphs. Finally, this shape theorem can be used to investigate a problem which is considered in structural analysis of fixed-access telecommunication networks, where we determine the limiting distribution of the length of the longest branch in the shortest-path tree extracted from a typical segment system if the intensity of network stations converges to zero.

Keywords: first-passage percolation; shape theorem; shortest-path tree; longest shortest path; random geometric graph

2010 Mathematics Subject Classification: Primary 60D05

Secondary 05C80; 05C10; 82B43

1. Introduction

We investigate a first-passage percolation model on a large class of connected, stationary and isotropic random geometric graphs, where the edge-passage times are given by the Euclidean lengths of the edges. The classical first-passage percolation model due to J. Hammersley and D. Welsh [14] considers shortest-path lengths on a randomly weighted lattice, where the edge weights form a sequence of independent and identically distributed (i.i.d.) non-negative random variables. More recently, the analysis of the asymptotic behaviour of such shortest-path lengths has been extended to geometrically irregular random geometric graphs, such as Poisson-Delaunay graphs, see Figure 1 for an illustration. While [27, 31, 32] consider the classical scenario of i.i.d. edge weights, such connected random geometric graphs give rise also to another natural first-passage percolation model, where the edge weights are determined by the Euclidean length of the edge [1, 2, 3, 5].

In the present paper, building on the work of [1, 3, 11], we show that not only the Poisson-Delaunay graph, but in fact a considerably larger class of connected random geometric graphs satisfies a strong linear growth property. To be more precise, considering the event that the growth of shortest-path lengths between

* Postal address: Institute of Stochastics, Ulm University, 89069 Ulm, Germany Tel.: +49-731-5031083 E-mail: christian.hirsch@uni-ulm.de

** Postal address: Orange Labs, 38-40, rue du Général Leclerc, 92794 Issy-les-Moulineaux, France Tel.: +33-(0)1 45 29 64 41 E-mail: catherine.gloaguen@orange.com

two (end-) points does not admit a linear upper bound in the Euclidean distance between the endpoints, we show in Theorem 1 that its probability tends to zero at least sub-exponentially fast as this distance tends to infinity.

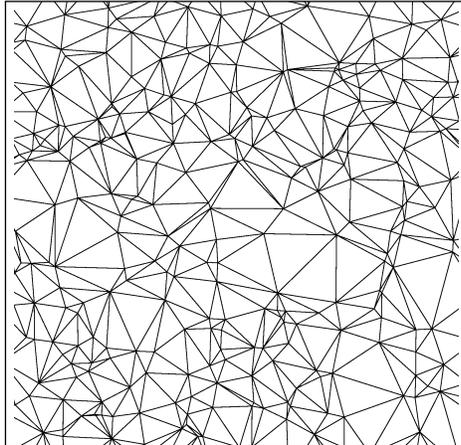


FIGURE 1: Realisation of a Delaunay graph generated by a homogeneous Poisson point process (cutout)

We continue to elaborate a variety of further implications of the strong linear growth property stated in Theorem 1. First, for a rather general class of stationary and isotropic random geometric graphs in \mathbb{R}^d , we show that this growth property implies a shape theorem for the Euclidean first-passage model defined by such random geometric graphs (Theorem 2). In particular, we extend the classical shape theorem, which has been derived in [18] for first-passage percolation on the lattice \mathbb{Z}^d (with i.i.d. edge weights), to a framework involving geometrically complex random graphs with non-independent edge lengths. Furthermore, in a two-dimensional setting, the growth property stated in Theorem 1 can be used to deduce the almost sure (a.s.) boundedness of cells defined by planar random geometric graphs (Theorem 3). In this way, the a.s. boundedness of cells of the creek-crossing graphs $(G_n)_{n \geq 2}$ introduced in [15] can be shown.

We also show how Theorem 2 can be used to investigate a problem which is considered in structural analysis of (wired) fixed-access telecommunication networks. In those networks, access points are located along the roads of urban or rural regions and each access point is dedicated to providing service to all users in some bounded region of the plane, which is referred to as its serving zone. Physical links from network users to access points are deployed along the shortest Euclidean path in the road graph, thus giving rise to a shortest-path connection tree representing the subgraph inside a serving zone, see e.g. [13, 33]. Cost estimation of the telecommunication network requires knowledge of structural properties of this tree. In the present paper, we show how our shape theorem stated in Theorem 2 (in conjunction with an asymptotic distributional result due to P. Calka [8]) can be used to determine the limiting distribution of the length of the longest branch in the shortest-path tree associated with a randomly chosen serving zone as the intensity of access points converges to zero (Theorem 4).

The present paper is organised as follows. First, in Section 2 we state our main results and introduce some general conditions on the considered random geometric graphs and the underlying point processes, which are used later on in the proofs of our results. In Section 3 we show that these conditions are satisfied for various well-known classes of random geometric graphs and point processes from stochastic geometry. Then, in Section 4, we provide a proof for the strong linear growth property stated in Theorem 1. Section 5 is devoted to the proof of the shape theorem and the boundedness of cells stated in Theorems 2 and 3, respectively. Finally, we conclude the paper with Section 6, where a proof of Theorem 4 is presented.

2. Main results

2.1. Random geometric graphs based on point processes

In classical models of first-passage percolation, one considers shortest-path lengths in independently marked lattices, but more recently also first-passage percolation on the Poisson-Delaunay graph has received considerable attention. While the papers [27, 31, 32] consider the scenario of independently marked edges, in [1] a spatially dependent marking using the Euclidean edge length is investigated not only for the Poisson-Delaunay graph, but in fact for a more general class of connected random geometric graphs whose vertices are given by a homogeneous Poisson point process in \mathbb{R}^2 . However, even in two dimensions important examples of connected random geometric graphs, such as the Poisson-Voronoi tessellation, are not based on a Poisson point process of vertices. Therefore, in the present paper, we state our results using the following general notion of random geometric graphs.

Denote by \mathbb{M} the family of all line segments in \mathbb{R}^d . This family forms a topological space in the Fell topology [30] and we denote by \mathcal{M} the Borel σ -algebra on \mathbb{M} generated by this topology. We write \mathbb{G} for the family of all simple counting measures φ on $\mathbb{R}^d \times \mathbb{M}$ such that $\varphi(B \times \mathbb{M})$ is finite for every bounded Borel set $B \subset \mathbb{R}^d$. Furthermore, we denote by \mathcal{G} the σ -algebra on \mathbb{G} that is generated by the evaluation maps $\varphi \mapsto \varphi(B \times M)$, where $B \subset \mathbb{R}^d$ is a Borel set in \mathbb{R}^d and $M \in \mathcal{M}$. Random variables with values in \mathbb{G} are called *random segment processes* or *random geometric graphs*. It will be convenient to identify elements $\varphi \in \mathbb{G}$ with their support, so that we can represent φ as $\varphi = \{(x_n, u_n)\}_{n \geq 1}$ for some $x_n \in \mathbb{R}^d$ and $u_n \in \mathbb{M}$.

In order to deal with a large variety of commonly used connected random geometric graphs, we do not need the notion of random segment processes in its entire generality, but it is convenient to introduce a more specific and restricted subclass. To be more precise, we consider random geometric graphs that are obtained from point processes in a deterministic way. For instance, the edge set of the Delaunay tessellation forms a geometric graph in \mathbb{R}^d whose vertices are given by a point process and whose edges are constructed by applying a deterministic connection rule. This observation also applies to the creek-crossing graphs $(G_n)_{n \geq 2}$ introduced in [15] which form a class of subgraphs of the Delaunay tessellation approximating the minimal spanning forest. Similarly, the Voronoi graph is defined as the edge set of a tessellation which is constructed from a given point process of cell centres by a deterministic rule.

All of these random geometric graphs have two important attributes in common. On the one hand, local changes in the underlying point process typically lead to local changes in the structure of the random geometric graph and, on the other hand, the resulting random geometric graphs consist of a single connected component with probability 1. We show that for such random geometric graphs shortest-path lengths along the edges grow at most linearly in the Euclidean distance of the endpoints of the paths.

Denote by \mathbb{N} the family of all locally finite sets in \mathbb{R}^d . In the following, we consider random geometric graphs in \mathbb{R}^d of the type $G = g(X)$, where X denotes a point process in \mathbb{R}^d which is stationary, isotropic and m -dependent, and $g : \mathbb{N} \rightarrow \mathbb{G}$ is a measurable mapping which is motion-covariant. In other words, we have $g(\alpha(\psi)) = \alpha(g(\psi))$ for all $\psi \in \mathbb{N}$ and all rigid motions $\alpha : \mathbb{R}^d \rightarrow \mathbb{R}^d$. Note that since g is motion-covariant, the random geometric graph G inherits from X the properties of stationarity and isotropy.

In the arguments used in the present paper, we need to make further suitable assumptions on G . In the following, it will be convenient to think of an element $\{(x_n, u_n)\}_{n \geq 1}$ of \mathbb{G} as the subset of \mathbb{R}^d formed by the union $\bigcup_{n \geq 1} (u_n + x_n)$. First, we need a certain growth condition allowing us to control the total length of the random geometric graph G inside cubic sampling windows (the total length in big windows should be positive and not too large, with high probability). Formally, the standard length of a line segment can be measured using the 1-dimensional Hausdorff measure ν_1 . Furthermore, the random geometric graph $G = g(X)$ should satisfy a suitable stability condition with respect to X , so that the configuration of G inside a bounded sampling window $W \subset \mathbb{R}^d$ does not depend on the configuration of X far away from the set W . Finally, we require a strong connectivity condition, in the sense that any two points on $G \cap W$ can be connected by a path on G which is contained in a suitable neighbourhood of the sampling window W . In order to state these additional assumptions on G more precisely, we use the following notion of occurrence with high probability. Let $(A_a)_{a > 1}$ be a family of events in a certain probability space $(\Omega, \mathcal{F}, \mathbb{P})$, which is

assumed to be complete. We say that the events A_a occur *with high probability* (whp) if

$$\liminf_{a \rightarrow \infty} \frac{\log(-\log(1 - \mathbb{P}(A_a)))}{\log a} > 0. \quad (1)$$

Note that the latter inequality is equivalent to the existence of constants $c_1, c_2 > 0$ such that $1 - \mathbb{P}(A_a) \leq c_1 \exp(-a^{c_2})$ for all $a > 1$. Furthermore, we use the following notation. For $x \in \mathbb{R}^d$ and $r \in (0, \infty]$ we denote by $Q_r(x) = [-r/2, r/2]^d + x$ the cube of side length r and centre x .

In the following, the existence of a suitable radius of stabilisation for the construction rule g will be crucial. Putting $\mathbb{Z}_{+, \infty} = ((0, \infty) \cap \mathbb{Z}) \cup \{\infty\}$ and denoting by o the origin in \mathbb{R}^d , a radius of stabilisation is defined to be a measurable function $b: \mathbb{N} \rightarrow \mathbb{Z}_{+, \infty}$ such that with probability 1, it holds that

$$g(X) \cap Q_1(o) = g((X \cap Q_{b(X)}(o)) \cup \psi) \cap Q_1(o) \quad (2)$$

for all locally finite $\psi \subset \mathbb{R}^d \setminus Q_{b(X)}(o)$, and that

$$\min\{b(X), n+1\} = \min\{b(X \cap Q_n(o) \cup \psi), n+1\}, \quad (3)$$

for all $n \in [1, \infty) \cap \mathbb{Z}$ and locally finite $\psi \subset \mathbb{R}^d \setminus Q_n(o)$. While (2) guarantees that the intersection $g(X) \cap Q_1(o)$ only depends on the point process X in the window $Q_{b(X)}(o)$, we use (3) in order to ensure that for $n \geq 1$ the event $\{b(X) \leq n\}$ only depends on the point process X in the window $Q_n(o)$. Now, assume that

(G1) the events $A_a^{(1)} = \{G \cap Q_a(o) \neq \emptyset\} \cap \{\nu_1(G \cap Q_1(o)) \leq a\}$ occur whp (growth condition),

(G2) the events $A_a^{(2)} = \{b(X) \leq a\}$ occur whp (stability condition),

(G3) the events $A_a^{(3)} = \{G \cap Q_{a/2}(o) \text{ is contained in a connected component of } G \cap Q_a(o)\}$ occur whp (connectivity condition).

In Section 3, we verify that these conditions are satisfied for the previously discussed examples of random geometric graphs. Note that condition (G3) is a modification of the asymptotic essential connectedness property introduced by D. Aldous, see [1]. Furthermore, the Borel-Cantelli lemma shows that condition (G3) implies a.s. connectivity of G .

The asymptotic behaviour of shortest-path lengths is a recurring theme in first-passage percolation and is also the content of the main result of the present paper. This result deals with the sub-exponential decay of the probability that such path lengths along the edges of G increase superlinearly in the Euclidean distance of their endpoints. To formulate it precisely, we put $e_1 = (1, 0, \dots, 0)^\top$ and $q(x) = \operatorname{argmin}_{y \in G} |x - y|$ for any $x \in \mathbb{R}^d$. If this is not unique, we take the lexicographically smallest point on G with this property. Furthermore, for $x, y \in \mathbb{R}^d$ we denote by $\ell(x, y)$ the length of the shortest Euclidean path between $q(x)$ and $q(y)$ on G .

Theorem 1. *Let G denote a random geometric graph in \mathbb{R}^d of the form $G = g(X)$ satisfying the conditions (G1)–(G3). Then there exists $u_0 \geq 1$ with*

$$\liminf_{\substack{ur \rightarrow \infty \\ u \geq u_0, r \geq 1}} \frac{\log(-\log \mathbb{P}(\ell(o, re_1) \geq ur))}{\log(ur)} > 0. \quad (4)$$

The proof of Theorem 1 is postponed to Section 4. Note that this theorem is an extension of a similar result which has been derived by D. Aldous for a class of planar graphs, see [1, 3]. Before we move on, we also remark that Theorem 1 contains two interesting special cases. On the one hand, we may fix r and consider the asymptotic behaviour of the tail probabilities $\mathbb{P}(\ell(o, re_1) \geq ur)$ as $u \rightarrow \infty$. In this case, Theorem 1 yields sub-exponential decay of the tail function of the length of the shortest path between two points at predefined locations of distance r , i.e. there exist constants $c_1, c_2 > 0$ such that $\mathbb{P}(\ell(o, re_1) \geq ur) \leq c_1 \exp(-u^{c_2})$ for all

$u > 1$. On the other hand, we can also fix $u \geq u_0$ and let $r \rightarrow \infty$. Then, as $r \rightarrow \infty$ the shortest-path length between points at distance r grows at most linearly in r whp.

We believe that Theorem 1 is useful for future research, since the issue of existence of short paths in random geometric graphs occurs in rather diverse contexts, such as the non-triviality of Bernoulli percolation on the Gabriel and relative neighbourhood graphs [6, 7] or the transience of random walks on random geometric graphs [29]. Furthermore, note that the framework of Theorem 1 can be extended to include also random geometric graphs generated by curved fibres, such as the dead leaves model or the Johnson-Mehl tessellation [17, 23]. However, as proving Theorem 1 only for random geometric graphs consisting of line segments simplifies the exposition, we restrict our attention to this special class of random fibre processes.

2.2. A general class of random geometric graphs

It turns out that the strong linear growth property (4) is satisfied not only by the random geometric graphs considered in Theorem 1, but also by the isotropic Poisson line tessellation in \mathbb{R}^2 , which does not fit into the framework of condition (G2), see Section 3.3. Therefore, in the present section we assume that G is an arbitrary stationary, ergodic and isotropic random geometric graph in \mathbb{R}^d for which (4) holds and which satisfies conditions (G1) and (G3). Theorems 2 and 3, whose proofs are postponed to Sections 5.1 and 5.2, respectively, provide two implications of property (4). For $r > 0$ and $x \in \mathbb{R}^d$, we denote by $B_r(x)$ the d -dimensional Euclidean ball with centre x and radius r and similarly, by $B_r^G(x) = \{y \in \mathbb{R}^d : \ell(x, y) \leq r\}$ the ball of radius r and centre x in the metric induced by the shortest-path lengths $\ell(x, y)$.

Theorem 2 supports the intuition that the notion of distance defined by the shortest-path lengths $\ell(x, y)$ behaves asymptotically as a scalar multiple of the ordinary Euclidean metric. This result can be regarded as a shape theorem for the first-passage percolation model, in which the passage time of an edge in G is given by its length. We refer the reader to [18, Theorem 1.7] for the classical statement in the situation of i.i.d. weights on the lattice \mathbb{Z}^d .

Theorem 2. *There exists a constant (the time constant) $\xi \geq 1$ such that for every $\varepsilon > 0$*

$$\mathbb{P}(B_{(1-\varepsilon)r}(o) \subset B_{\xi r}^G(o) \subset B_{(1+\varepsilon)r}(o)) \text{ for all sufficiently large } r) = 1. \quad (5)$$

The second implication of property (4) deals with the a.s. boundedness of cells defined by random geometric graphs in \mathbb{R}^2 , where for a planar random geometric graph G in \mathbb{R}^2 we call the connected components of $\mathbb{R}^2 \setminus G$ the *cells* of G .

Theorem 3. *Let $d = 2$. Then, with probability 1, all cells of G are bounded.*

2.3. An application to shortest-path trees in spatial telecommunication networks

Last but not least, for $d = 2$ we provide an application of Theorem 2 to a problem which is considered in structural analysis of fixed-access telecommunication networks. In particular, we show how Theorem 2 can be used to determine the limiting distribution of the length of the longest branch in a typical shortest-path tree if the intensity of access points converges to zero.

We start by recalling some notation and definitions related with this kind of problems and refer the reader to [25] for details. Let G be a stationary, isotropic and ergodic random geometric graph in \mathbb{R}^2 satisfying (4) and conditions (G1) and (G3) of Section 2.1. We write $\gamma = \mathbb{E}\nu_1(G \cap [0, 1]^2) > 0$ for its *length intensity*, and G^* for the *Palm version* of G with respect to $\nu_1(\cdot \cap G)$. Recall that G^* is a random geometric graph whose distribution is determined by

$$\mathbb{E}h(G^*) = \frac{1}{\gamma} \mathbb{E} \int_{G \cap [0, 1]^2} h(G - x) \nu_1(dx),$$

where $h : \mathbb{G} \rightarrow [0, \infty)$ is any \mathcal{G} -measurable function. By X_λ we denote a Cox process on G^* whose random intensity measure is given by $\lambda \nu_1(\cdot \cap G^*)$, for some linear intensity $\lambda > 0$. Denote by $\Xi_{0, \lambda}$ the zero-cell of the Voronoi tessellation on $X_\lambda \cup \{o\}$ and write $S^* = \Xi_{0, \lambda} \cap G^*$ for the *typical segment system* within $\Xi_{0, \lambda}$. Since shortest paths do not contain cycles, they induce a natural tree structure on the set of points of G^* for which the shortest path to o is unique. This tree is sometimes referred to as *shortest-path tree*.

For practical applications to telecommunication networks it is desirable to have knowledge about a variety

of distributional properties of typical segment systems. Such properties could help to find useful approximate simulation algorithms (deduced from limit theorems) that allow for a rapid creation of such graphs without having to implement concepts of stochastic geometry. In the following, we denote by $Z(\lambda) = \sup_{x \in S^*} \ell(o, x)$ the length of the longest shortest path among all shortest paths emanating from the origin o and ending at an element of S^* . Although there is only little hope to obtain an explicit analytical formula for the distribution of $Z(\lambda)$ when considering general values of $\lambda \in (0, \infty)$, we show how Theorem 2 in conjunction with a distributional result due to P. Calka [8] on the circumradius of typical Poisson-Voronoi cells can be used to obtain an explicit asymptotic formula in the case when $\lambda \rightarrow 0$.

Theorem 4. *Let R be the radius of the smallest circle centred at the origin and containing the zero-cell of the Voronoi tessellation on $Y \cup \{o\}$, where Y is a homogeneous Poisson point process with intensity γ . Then $\sqrt{\lambda}Z(\lambda) \xrightarrow{D} \xi R$ as $\lambda \rightarrow 0$, where $\xi = \lim_{n \rightarrow \infty} \mathbb{E}\ell(o, ne_1)/n$ is the time constant appearing in Theorem 2.*

The proof of Theorem 4 will be provided in Section 6. To go further in the analysis of connection trees, it seems promising to consider not only the longest shortest path in a typical serving zone, but e.g. also the joint distribution of the lengths of the main branches in each of the two subtrees rooted at the origin. They may be considered as backbones of the entire connection tree. This problem is considered in [16] and [24] in greater detail from a theoretical and practical point of view, respectively.

Moreover, for practical applications to telecommunication networks, it is important not only to know the behaviour of the longest shortest path as $\lambda \rightarrow 0$, but also to have some information about its length for arbitrary values of $\lambda > 0$. Since it seems rather unlikely that there exists an explicit analytical formula for the distribution of the longest shortest-path length $Z(\lambda)$, parametric density functions are fitted to simulated data [24]. However, these approximative densities rely on Monte Carlo simulations, which become increasingly time-consuming as one approaches the asymptotic setting. Hence, our result is useful for certain parameter constellations, where standard Monte Carlo simulations are not be feasible.

3. Examples of connected graphs

In this section, we show that many well-known connected random geometric graphs satisfy the growth, stability and connectivity conditions (G1)-(G3) introduced in Section 2.1. We consider the Delaunay graph, the family of creek-crossing graphs $(G_n)_{n \geq 2}$ introduced in [15] and the Voronoi graph in arbitrary dimensions. Finally, we show that the (two-dimensional) isotropic Poisson line tessellation has property (4). Note, however, that the Poisson line tessellation does not fit naturally into the framework of point-process-based random geometric graphs described in Section 2.1 and also exhibits long-range dependencies which are incompatible with the stability condition (G2) of Section 2.1.

3.1. Delaunay graph Del and the creek-crossing graphs G_n , $n \geq 2$

For $\varphi \subset \mathbb{R}^d$ locally finite and $B \subset \mathbb{R}^d$ a Borel set, we denote the number of elements of φ in B by $\varphi(B) = \#(\varphi \cap B)$. In the following we assume that X is a stationary, isotropic and m -dependent point process in \mathbb{R}^d satisfying the following additional conditions. Suppose that

(D1) for $a > 1$ the events $\{X \cap Q_a(o) \neq \emptyset\} \cap \{X(Q_1(o)) \leq a\}$ occur whp, and

(D2) the second factorial moment measure of X is absolutely continuous with respect to $2d$ -dimensional Lebesgue measure and its density $\rho(x, y)$ is bounded from above by some constant $c > 0$.

The homogeneous Poisson point process in \mathbb{R}^d with intensity $\lambda_p > 0$ obviously satisfies the above conditions.

Recall that for any $\varphi \subset \mathbb{R}^d$ locally finite, the Delaunay graph $\text{Del}(\varphi)$ denotes a graph with vertex set φ , where two vertices $x, y \in \varphi$ are connected by an edge in $\text{Del}(\varphi)$ if there exists a ball $B \subset \mathbb{R}^d$ such that $x, y \in B$ but $\varphi \cap \text{int } B = \emptyset$. Here $\text{int } B$ denotes the topological interior of B . Furthermore, for any $\varphi \subset \mathbb{R}^d$ locally finite, $G_n(\varphi)$ denotes a graph with vertex set φ , where two vertices $x, y \in \varphi$ are connected by an edge in $G_n(\varphi)$ if there do not exist an integer $k \leq n$ and vertices $x_0 = x, x_1, \dots, x_k = y \in \varphi$ such that $|x_i - x_{i+1}| < |x - y|$ for all $i \in \{0, \dots, k-1\}$, see [15]. To begin with, we state an easy result for the maximum length of the edges in $\text{Del}(X)$ that intersect a given bounded set. Since $G_n(X) \subset \text{Del}(X)$ this also

yields useful information for the creek-crossing graphs $G_n(X)$, $n \geq 2$. For $c_1, c_2 > 0$ we define

$$b_{c_1, c_2}(\varphi) = \inf \{n \geq c_2 : \varphi \cap Q_{n,i} \neq \emptyset \text{ for all } i \in \{1, \dots, \lfloor n^{c_1} \rfloor^d\}\}, \quad \varphi \in \mathbb{N}, \quad (6)$$

where $Q_{n,1}, \dots, Q_{n, \lfloor n^{c_1} \rfloor^d}$ denotes a subdivision of $Q_n(o)$ into $\lfloor n^{c_1} \rfloor^d$ congruent sub-cubes. Note that b_{c_1, c_2} satisfies (3).

Lemma 1. *Let $\beta \in (0, 1)$ be an arbitrary fixed number and write b_β instead of $b_{1-\beta/2, c}$. Then, there exists $c' > 1$ such that for all $c > c'$ for $a > 1$ the events $\{b_\beta(X) \leq a\}$ occur whp. Furthermore, with probability 1 it holds that $|X_1 - X_2| < b_\beta(X)^\beta$ or $[X_1, X_2] \cap Q_1(o) = \emptyset$ for all locally finite $\psi \subset \mathbb{R}^d \setminus Q_{b_\beta(X)}(o)$ and $X_1, X_2 \in (X \cap Q_{b_\beta(X)}(o)) \cup \psi$ such that $[X_1, X_2]$ forms an edge in $\text{Del}((X \cap Q_{b_\beta(X)}(o)) \cup \psi)$.*

Proof. For $n > 1$ subdivide $Q_n(o)$ into $k = \lfloor n^{1-\beta/2} \rfloor^d$ congruent sub-cubes $Q_{n,1}, \dots, Q_{n,k}$ of side length $n/\lfloor n^{1-\beta/2} \rfloor$. Next, observe that there exists $c > 1$ such that for all $n \geq c$, any ball which intersects $Q_1(o)$ and whose diameter is at least n^β contains at least one of the cubes $Q_{n,1}, \dots, Q_{n,k}$. Furthermore, if $X_1, X_2 \in (X \cap Q_n(o)) \cup \psi$ are such that $[X_1, X_2] \cap Q_1(o) \neq \emptyset$ where $|X_1 - X_2| \geq n^\beta$ and X_1, X_2 are connected by an edge in $\text{Del}(X \cap Q_n(o) \cup \psi)$, then there exists a ball B of diameter at least n^β satisfying $(X \cap Q_n(o) \cup \psi) \cap \text{int} B = \emptyset$. Finally, note that for every $a > 1$ we have $\mathbb{P}(b_\beta(X) > a) \leq \sum_{i=1}^k \mathbb{P}(X \cap Q_{\lfloor a \rfloor, i} = \emptyset)$, so that condition (D1) implies that for $a > 1$ the events $\{b_\beta(X) \leq a\}$ occur whp.

We now verify the conditions (G1)-(G3) of Section 2.1 for the graphs $\text{Del}(X)$ and $G_n(X)$, respectively.

Lemma 2. *Let $n \geq 2$ be an arbitrary fixed number. Then, for $a > 1$ the events $G_n(X) \cap Q_a(o) \neq \emptyset$ and therefore also the events $\text{Del}(X) \cap Q_a(o) \neq \emptyset$ occur whp. Moreover, for $a > 1$ the events $\nu_1(\text{Del}(X) \cap Q_1(o)) \leq a$ and therefore also the events $\nu_1(G_n(X) \cap Q_1(o)) \leq a$ occur whp. In other words, for $G = \text{Del}(X)$ and $G = G_n(X)$ the events $A_a^{(1)}$ in condition (G1) occur whp.*

Proof. As $X \subset G_n(X) \subset \text{Del}(X)$ the first assertion follows from condition (D1). Due to the subgraph relation $G_n(X) \subset \text{Del}(X)$ it suffices to prove the second claim when $G = \text{Del}(X)$. Observe that by Lemma 1 whp the length of any edge intersecting $Q_1(o)$ is at most $a^{1/(2d+3)}$. Furthermore, by condition (D1) we have $X(Q_{3a^{1/(2d+3)}}(o)) \leq a^{(d+1)/(2d+3)}$ whp, so that $\nu_1(\text{Del}(X) \cap Q_1(o)) \leq \sqrt{d} a^{(2d+2)/(2d+3)} \leq a$ whp.

Lemma 3. *Let $G = \text{Del}(X)$. Then, there exists $c > 1$ such that the function $b_{3/4, c} : \mathbb{N} \rightarrow \mathbb{Z}_{+, \infty}$ introduced in (6) satisfies (2) and such that for $a > 1$ the events $\{b_{3/4, c}(X) \leq a\}$ occur whp.*

Proof. We can use similar arguments as in the proof of Lemma 1. For $n > 1$ subdivide $Q_n(o)$ into $k = \lfloor n^{3/4} \rfloor^d$ congruent sub-cubes $Q_{n,1}, \dots, Q_{n,k}$ of side length $n/\lfloor n^{3/4} \rfloor$. Next, observe that there exists $c > 1$ such that for all $n \geq c$, any ball of diameter at least \sqrt{n} intersecting $Q_1(o)$ contains at least one of these sub-cubes. Furthermore, if $\psi \subset \mathbb{R}^d \setminus Q_{b_{3/4, c}(X)}(o)$ and $X_1, X_2 \in (X \cap Q_n(o)) \cup \psi$ are such that $[X_1, X_2] \cap Q_1(o) \neq \emptyset$ and $[X_1, X_2]$ forms an edge in exactly one of the two graphs $\text{Del}(X \cap Q_n(o))$ and $\text{Del}(X \cap Q_n(o) \cup \psi)$, then there exists a ball $B \subset \mathbb{R}^d$ intersecting both $Q_1(o)$ and $\mathbb{R}^d \setminus Q_n(o)$ such that $X \cap B = \emptyset$. Finally, note that for every $a > 1$ we have $\mathbb{P}(b_{3/4, c}(X) > a) \leq \sum_{i=1}^k \mathbb{P}(X \cap Q_{\lfloor a \rfloor, i} = \emptyset) \leq \lfloor a^{3/4} \rfloor^d \mathbb{P}(X \cap Q_{\lfloor a \rfloor, 1} = \emptyset)$, so that condition (D1) implies that for $a > 1$ the events $\{b_{3/4, c}(X) \leq a\}$ occur whp.

Lemma 4. *Let $G = G_n(X)$ for some $n \geq 2$. Then, there exists $c > 4(n+1)^2$ such that the measurable function $b^{(n)} = b_{3/4, c}$ satisfies (2) and for $a > 1$ the events $\{b^{(n)}(X) \leq a\}$ occur whp.*

Proof. Indeed, suppose we could find $\psi \subset \mathbb{R}^d \setminus Q_{b^{(n)}(X)}(o)$ locally finite and $X_1, X_2 \in X \cap Q_{\sqrt{b^{(n)}(X)}}(o)$ such that $|X_1 - X_2| \leq \sqrt{b^{(n)}(X)}$ and $[X_1, X_2] \cap Q_1(o) \neq \emptyset$, where $[X_1, X_2]$ forms an edge in exactly one of the two graphs $G_n(X \cap Q_{b^{(n)}(X)}(o))$ and $G_n(X \cap Q_{b^{(n)}(X)}(o) \cup \psi)$. However, since $|X_1 - X_2| \leq \sqrt{b^{(n)}(X)}$, the existence of an edge between X_1 and X_2 only depends on the $X \cap Q_{2(n+1)\sqrt{b^{(n)}(X)}}(o) \subset X \cap Q_{b^{(n)}(X)}(o)$.

This contradiction implies that $b^{(n)}$ satisfies (2) so that an application of Lemma 2 completes the proof.

Let again $G = G_n(X)$ for some $n \geq 2$. Our next goal is to show that for $a > 1$ the events $A_a^{(3)}$ occur whp. To prove this claim, we need a result on generalised descending chains. This notion is introduced is introduced

in [15] and is closely related to the concept of descending chains discussed in [9]. Let $b > 0$ and $\varphi \subset \mathbb{R}^d$ be locally finite. We say that a finite sequence $x_1, \dots, x_k \in \varphi$ forms a *finite b -bounded generalised descending chain* in φ if there exists an ordered set $I = \{i_1, \dots, i_{k'}\} \subset \{1, \dots, k\}$ with the properties $|i_{j+1} - i_j| \leq 2$ for all $j \in \{0, \dots, k' - 1\}$, $0 < |x_i - x_{i+1}| \leq b$ for all $i \in \{1, \dots, k - 1\}$ and $|x_{i_j+1} - x_{i_j}| < |x_{i_{j-1}+1} - x_{i_{j-1}}|$ for all $j \in \{2, \dots, k'\}$, where we use the convention $i_0 = 0$.

Lemma 5. *Let $A : \mathbb{R}^d \times [0, \infty)^2 \times \mathbb{N} \rightarrow \{0, 1\}$ denote the function with the property that for $b, r > 0$, $\varphi \subset \mathbb{R}^d$ locally finite and $x \in \varphi$ it holds that $A(x, b, r, \varphi) = 1$ if and only if there exists a b -bounded generalised descending chain in φ starting at x and leaving the ball $B_r(x)$. Then, for $b > 1$ the events $\{A(\eta, b, 4db^{2d+3}, X) = 0\}$ for all $\eta \in X \cap Q_1(o)$ occur whp.*

Proof. Let $p \in (0, 1)$ and consider Bernoulli site percolation on the lattice with set of sites \mathbb{Z}^d and edges given by $\{\{x, y\} \subset \mathbb{Z}^d : |x - y|_\infty \leq 1\}$, where $|z|_\infty = \max_{i \in \{1, \dots, d\}} |z_i|$ for $z = (z_1, \dots, z_d) \in \mathbb{R}^d$. By Peierl's argument (see e.g. [26, Lemma 9.3]) the probability that the open cluster at the origin contains at least k sites can be bounded from above by $(2^{3^d - 1} p)^k$. We choose p such that $\gamma = 2^{3^d - 1} p < 1$ and define suitable site-percolation models. Let $b > 0$ be an arbitrary fixed number. For $k \geq 0$, $\varepsilon > 0$ and $w \in \mathbb{Z}^d$ we say that w is (k, ε) -open if there exists $v \in Q_{4b}(4bw) \cap X$ with $X(B_{(k+1)\varepsilon}(v) \setminus B_{k\varepsilon}(v)) > 0$. For $\varepsilon = b^{-2d}$ and $k \geq 1$ with $k\varepsilon \leq b$ the probability that an arbitrary site $w \in \mathbb{Z}^d$ is (k, ε) -open can be bounded from above in the following way. Let ν_d be the Lebesgue measure in \mathbb{R}^d . Then, the probability that w is (k, ε) -open is at most

$$\mathbb{E} \sum_{\eta \in X} \sum_{\eta' \in X \setminus \{\eta'\}} 1_{Q_{4b}(4bw)}(\eta) 1_{B_{(k+1)\varepsilon}(\eta) \setminus B_{k\varepsilon}(\eta)}(\eta') \leq c \int_{Q_{4b}(4bw)} \nu_d(B_{(k+1)\varepsilon}(u) \setminus B_{k\varepsilon}(u)) du,$$

and the latter expression is bounded from above by

$$c(4b)^d \kappa_d \varepsilon^d ((k+1)^d - k^d) \leq 2^{3d} c \kappa_d \varepsilon b^d (k\varepsilon)^{d-1} \leq 2^{3d} c \kappa_d b^{-1},$$

where κ_d denotes the volume of the unit ball in \mathbb{R}^d . A similar upper bound can be deduced for $k = 0$. Thus, we see that by choosing b sufficiently large (independent of w and k), the probability of a site being open can be made as small as desired. Furthermore, for sufficiently large b these site percolation models are 2-dependent. In particular, by [20, Theorem 0.0], if b is chosen sufficiently large, then the site-percolation model of (k, ε) -open sites can be dominated from above by an independent Bernoulli site percolation model at probability p chosen as above. Now assume the existence of $\eta_1 \in X \cap Q_1(o)$ such that $A(\eta_1, b, 4db^{2d+3}, X) = 1$. Then there exists a b -bounded generalised descending chain $\eta_1, \eta_2, \dots, \eta_n$ with $\eta_n \notin B_{4db^{2d+3}}(\eta_1)$. Define a map $f : \{1, \dots, n\} \rightarrow \mathbb{Z}^d \times \{0, \dots, \lceil b^{2d+1} \rceil\}$, $i \mapsto (z, j)$, where z is determined by $\eta_i \in Q_{4b}(4bz)$ and $j = \lceil b^{2d} |\eta_i - \eta_{i+1}| \rceil$ if $i \in I$ and $j = \lceil b^{2d} |\eta_{i+1} - \eta_{i+2}| \rceil$ otherwise. Note that the composition of f and the projection π_2 to the second argument defines a monotonously decreasing function. Furthermore, the image of the composition of f with the projection π_1 to the first component is of size at least b^{2d+2} (otherwise we could not reach $\mathbb{R}^d \setminus B_{4db^{2d+3}}(\eta_1)$ from $Q_1(o)$). Thus, we conclude the existence of at least one $j \in \{0, \dots, \lceil b^{2d+1} \rceil\}$ satisfying $\#\pi_1((\pi_2 \circ f)^{-1}(\{j\})) \geq b$, so that

$$\begin{aligned} \mathbb{P}(A(\eta, b, 4db^{2d+3}, X) = 1 \text{ for some } \eta \in X \cap Q_1(o)) \\ &\leq \sum_{j=0}^{\lceil b^{2d+1} \rceil} \mathbb{P}(\text{there exists a } (j, b^{-2d})\text{-open cluster inside } Q_{db^{2d+2}}(o) \text{ of size at least } b) \\ &\leq \sum_{j=0}^{\lceil b^{2d+1} \rceil} \sum_{z \in Q_{db^{2d+2}}(o) \cap \mathbb{Z}^d} \mathbb{P}(\text{the } (j, b^{-2d})\text{-open cluster at } z \text{ has size at least } b). \end{aligned}$$

Since the latter expression is at most $(\lceil b^{2d+1} \rceil + 1)(db^{2d+2})^d \gamma^b$, this completes the proof.

Furthermore, we need the following auxiliary result, see also [1].

Lemma 6. *Let $a > 1$ and $\varphi \subset \mathbb{R}^d$ be locally finite. Furthermore, let $\eta, \eta' \in \varphi$ be such that $2n|\eta - \eta'| \leq a$, where η, η' are contained in different connected components of $G_n(\varphi) \cap B_a(\eta)$. Then, $A(\eta, n|\eta - \eta'|, a/2, \varphi) = 1$, i.e. there exists an $n|\eta - \eta'|$ -bounded generalised descending chain starting at η and leaving the ball $B_{a/2}(\eta)$.*

Proof. We construct the desired chain $x_0, x'_0, x_1, x'_1, \dots$ recursively, starting with $x_0 = \eta$ and $x'_0 = \eta'$. This construction will ensure that for all $k \geq 0$ the sites x_k, x'_k belong to different connected components of $G_n(\varphi) \cap B_a(\eta)$ and we stop the construction as soon as $|y - \eta| \geq a/2$ for $y = x_k$ or $y = x'_k$. Suppose that x_k and x'_k have been constructed. By assumption, we know that $\{x_k, x'_k\}$ does not constitute an edge in $G_n(\varphi) \cap B_a(\eta)$. Thus, there exist $z_0 = x_k, z_1, \dots, z_j = x'_k \in \varphi$ with $j \leq n$ and $|z_i - z_{i+1}| < |x_k - x'_k|$ for all $1 \leq i \leq j-1$. As $2n|\eta - \eta'| \leq a$, we conclude that $z_i \in B_a(\eta) \cap \varphi$ for all $0 \leq i \leq j$. By assumption, there exists at least one index i_0 such that z_{i_0} and z_{i_0+1} belong to different connected components of $G_n(\varphi) \cap B_a(\eta)$. Then we define $x_{k+1} = z_{i_0}$ and $x'_{k+1} = z_{i_0+1}$.

For $r > 0$ and $\varphi \subset \mathbb{R}^d$ locally finite, we denote by $G(\varphi, r)$ the graph on the vertex set φ , where $x_1, x_2 \in \varphi$ are connected by an edge if and only if $|x_1 - x_2| < r$.

Lemma 7. *Let $\alpha \in (0, 1)$. Then, for $a > 1$ the graphs $G(X \cap Q_a(o), a^\alpha)$ are connected whp.*

Proof. Subdivide $Q_a(o)$ into $k = \lceil (d+1)a^{1-\alpha} \rceil^d$ sub-cubes $Q_{a,1}, \dots, Q_{a,k}$ so that any points in two neighbouring cubes (i.e., cubes sharing a $(d-1)$ -dimensional face) are at distance at most a^α . Thus, if each of these cubes contains at least one element from X , then $G(X \cap Q_a(o), a^\alpha)$ is connected and we obtain

$$\mathbb{P}(G(X \cap Q_a(o), a^\alpha) \text{ not connected}) \leq \mathbb{P}(X(Q_{a,i}) = \emptyset \text{ for some } i \in \{1, \dots, k\}),$$

which is at most $k\mathbb{P}(X(Q_{a,1}) = \emptyset)$. An application of (D1) now completes the proof.

Lemma 8. *Let $G = G_n(X)$ for some $n \geq 2$. Then, for $a > 1$ the events $A_a^{(3)}$ occur whp.*

Proof. If $A_a^{(3)}$ does not occur, then we may assume by Lemmas 1 and 7 that there exist $X_1, X_2 \in X \cap Q_{a/2+\sqrt{a}}(o)$ such that $|X_1 - X_2| \leq a^{1/(2d+4)}$, where X_1, X_2 are contained in different connected components of $G_n(X) \cap B_{a/4}(X_1) \subset G_n(X) \cap Q_a(o)$. In particular, Lemma 6 implies that $A(X_1, na^{1/(2d+4)}, a/8, X) = 1$. An application of Lemma 5 therefore completes the proof.

Due to the relation $G_n(X) \subset \text{Del}(X)$, the statement of Lemma 8 is also true for $G = \text{Del}(X)$.

3.2. Voronoi tessellation

Let $\varphi \subset \mathbb{R}^d$ be locally finite and define $\text{Vor}(\varphi) \subset \mathbb{R}^d$ to be the geometric graph obtained by considering the edge set of the Voronoi tessellation with centres in φ . To any $x \in \varphi$ we can associate the cell $\{y \in \mathbb{R}^d : |x - y| \leq \inf_{x' \in \varphi} |x' - y|\}$, and we define $\text{Vor}(\varphi)$ as the union of the edges of all such cells. Let X be a stationary, isotropic and m -dependent point process in \mathbb{R}^d , and let $G = \text{Vor}(X)$. Then, in contrast to the random geometric graph considered in Section 3.1, the point process X does not describe the vertices of the graph $G = \text{Vor}(X)$, but the locations of its cell centres. In this subsection, we make the following additional assumption on X . Suppose that

(V) for $a > 1$ the events $\{X \cap Q_a(o) \neq \emptyset\} \cap \{X(Q_1(o)) \leq a\}$ occur whp.

To begin with, we verify one part of condition (G1).

Lemma 9. *For $a > 1$ the events $\nu_1(\text{Vor}(X) \cap Q_1(o)) \leq a$ occur whp.*

Proof. Subdivide $Q_{(4d+1)a}(o)$ into $k = (4d+1)^d$ congruent sub-cubes $Q_{a,1}, \dots, Q_{a,k}$ of side length a and write $A_a = \bigcap_{i=1}^k \{X(Q_{a,i}) \geq 1\}$. Choosing an odd number of subcubes is convenient as it guarantees that the cube $Q_a(o)$ is a member of this decomposition. The dimension d needs to enter the number of elements in this decomposition, since also the diameter of the unit cube increases in d . We conclude from condition (V) that for $a > 1$ the events A_a occur whp. Furthermore, provided that A_a holds, the following is true: (i) if a Voronoi cell has non-empty intersection with $Q_1(o)$ then its centre is contained in $Q_{(4d+1)a}(o)$, and (ii) each edge intersecting $Q_1(o)$ is determined by a collection of d adjacent cells. Indeed, (ii) follows from

basic linear algebra and to show (i), we proceed as follows. Let $\eta \in X$ be such that there exists $\eta' \in Q_1(o)$ contained in the Voronoi cell associated with η . By assumption, $X \cap Q_a(o) \neq \emptyset$, so that $|\eta - \eta'| \leq \sqrt{d}a$, implying that $\eta \in Q_{(4d+1)a}(o)$. Therefore, (provided that A_a holds) the number of edges in $\text{Vor}(X) \cap Q_1(o)$ is bounded from above by $X(Q_{(4d+1)a}(o))^d$, so that $\nu_1(\text{Vor}(X) \cap Q_1(o)) \leq \sqrt{d}X(Q_{(4d+1)a}(o))^d$. Hence,

$$\begin{aligned} & \mathbb{P}(\nu_1(\text{Vor}(X) \cap Q_1(o)) > a^{d^2+3d}) \\ & \leq \mathbb{P}(A_a^c) + \mathbb{P}(\{\nu_1(\text{Vor}(X) \cap Q_1(o)) \leq \sqrt{d}X(Q_{(4d+1)a}(o))^d\} \cap \{\nu_1(\text{Vor}(X) \cap Q_1(o)) > a^{d^2+3d}\}) \\ & \leq \mathbb{P}(A_a^c) + \mathbb{P}(X(Q_{(4d+1)a}(o)) > a^{d+2}), \end{aligned}$$

so that an application of condition (V) completes the proof.

Next, we prove sub-exponential decay of $\mathbb{P}(\text{Vor}(X) \cap Q_a(o) = \emptyset)$, $\mathbb{P}(b(X) > a)$, and $1 - \mathbb{P}(A_a^{(3)})$ as $a \rightarrow \infty$. For $a > 1$ subdivide $Q_a(o)$ into $k = (8d+1)^d$ congruent sub-cubes $Q_{a,1}, \dots, Q_{a,k}$ of side length $a/(8d+1)$ and put $b(\varphi) = \inf \{n \geq 2 : \varphi \cap Q_{n,i} \neq \emptyset \text{ for all } i \in \{1, \dots, k\}\}$, where $\varphi \in \mathbb{N}$. First note that b satisfies (3). Moreover, for the same reasons as those provided in Lemma 9, it is convenient to consider a subdivision into an odd number of cubes, which is increasing in the dimension d .

Lemma 10. *The function $b : \mathbb{N} \rightarrow \mathbb{Z}_{+, \infty}$ introduced above satisfies (2). Moreover, for $a > 1$ the events $\text{Vor}(X) \cap Q_a(o) \neq \emptyset$, $\{b(X) \leq a\}$ and $A_a^{(3)}$ occur whp.*

Proof. We write $A_a = \bigcap_{i=1}^k \{X(Q_{a,i}) \geq 1\}$ and conclude from condition (V) that the events A_a and $\{b(X) \leq a\}$ occur whp. If A_a holds, then (i) the centre of any Voronoi cell intersecting $Q_1(o)$ is contained in $Q_{a/2}(o)$, (ii) the centre of any Voronoi cell intersecting $Q_{a/2}(o)$ is contained in $Q_{3a/4}(o)$ and (iii) the Voronoi cell associated with any $X_n \in X \cap Q_{3a/4}(o)$ is contained in $Q_a(o)$. We provide a proof of (iii), noting that (i) and (ii) can be proven by similar arguments. Indeed, let $\eta \in \mathbb{R}^d \setminus Q_a(o)$ be arbitrary and denote by P the intersection point of the line segment $[X_n, \eta]$ and $\partial Q_a(o)$. Let $i \in \{1, \dots, k\}$ be such that $P \in Q_{a,i}$ and choose an arbitrary $X_0 \in X \cap Q_{a,i}$. Then

$$|\eta - X_0| - |\eta - X_n| \leq |\eta - P| + |P - X_0| - |\eta - P| - |P - X_n| \leq a((\sqrt{d}+1)/(8d+1) - 1/8),$$

which is negative for $d \geq 2$, so that η is not contained in the cell associated with X_n . On the one hand, (i)-(iii) imply that b satisfies (2). On the other hand, as $A_a^{(3)}$ and $\text{Vor}(X) \cap Q_a(o) \neq \emptyset$ are implied by the joint occurrence of (ii) and (iii), we see that also the events $A_a^{(3)}$ and $\text{Vor}(X) \cap Q_a(o) \neq \emptyset$ occur whp.

3.3. Poisson line tessellation

In this subsection we show that the linear growth property (4) holds for the isotropic two-dimensional Poisson line tessellation. Although conditions (G1) and (G3) could be verified using similar arguments as in Lemma 11 below, we conjecture that condition (G2) (or some variant thereof) does not hold due to the long-range dependence inherent to the Poisson line model. However, as we will see, it is quite simple to check (4) directly. To be more precise, we consider the planar graph formed by the union of lines in an isotropic Poisson line process, which is defined as follows. Let $\{(R_n, U_n)\}_{n \geq 1} \subset \mathbb{R} \times [0, \pi)$ denote an independently marked Poisson point process in \mathbb{R} with intensity $\lambda > 0$, where the marks are uniformly distributed on $[0, \pi)$. Then the system of random lines $\{\ell_n\}_{n \geq 1}$ defined by $\ell_n = \{(x, y) \in \mathbb{R}^2 : x \cos U_n + y \sin U_n = R_n\}$, $n \geq 1$ is called an *isotropic Poisson line process*.

Lemma 11. *Let G be the edge set of the tessellation induced by an isotropic Poisson line process. Then property (4) holds.*

Proof. For $r, u > 1$ denote by $E_{r,u}$ the event that there exist four random lines $\{\ell_{n_i}\}_{1 \leq i \leq 4}$ of the Poisson line process such that they form the extensions of the edges of a quadrilateral Ξ satisfying $\{q(o), q(re_1)\} \subset \Xi \subset Q_{12ur}(o)$, where the notation $q(\cdot)$ was introduced in Section 2. Observe that if $E_{r,u}$ occurs, then $\ell(o, re_1) \leq 2\sqrt{2} \cdot 12ur + 4 \cdot 12ur$, where the notation $\ell(\cdot, \cdot)$ was also introduced in Section 2. Thus, it suffices to find sub-exponential bounds for $\mathbb{P}(E_{r,u}^c)$. We denote by $E_{r,u}^{(1)}$ the event that there exists a line ℓ_1 of

the Poisson line process whose angle is contained in $[\pi/2 - \pi/24, \pi/2 + \pi/24]$ and that intersects the ball $B_{\sqrt{ur}}((r + ur)e_1)$. Furthermore, we denote by $E_{r,u}^{(i)}$ the event obtained from $E_{r,u}^{(1)}$ by applying a rotation of angle $(i - 1)\pi/2$ and centre o . See Figure 2 for an illustration of the event $\bigcap_{i=1}^4 E_{r,u}^{(i)}$.

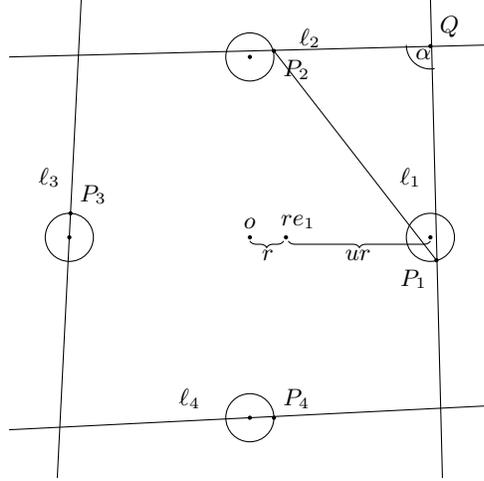


FIGURE 2: Occurrence of the event $\bigcap_{i=1}^4 E_{r,u}^{(i)}$

We claim that the existence of $u_0 > 1$ such that for all $u \geq u_0$ and for all sufficiently large ur the event $\bigcap_{i=1}^4 E_{r,u}^{(i)}$ implies $E_{r,u}$. The inclusion $\{q(o), q(re_1)\} \subset \Xi$ is clear. To prove $\Xi \subset Q_{12ur}(o)$ choose an arbitrary intersection point $P_1 \in \ell_1 \cap \partial B_{\sqrt{ur}}((r + ur)e_1)$. Similarly, choose P_2 as an intersection point of ℓ_2 with the circle $\partial B_{\sqrt{ur}}((r + ur)e_2)$ and put $\{Q\} = \ell_1 \cap \ell_2$. Using elementary geometry we see that for all ur sufficiently large the angle $\alpha = \angle P_2QP_1$ forms the largest angle in the triangle $\triangle P_2P_1Q$ and that $|P_1 - P_2| \leq 4ur$, see Figure 2. In particular, the point Q is contained in $Q_{12ur}(o)$. Since the same is true for $\ell_2 \cap \ell_3$, $\ell_3 \cap \ell_4$ and $\ell_4 \cap \ell_1$ we see that $E_{r,u}$ holds. Therefore, it remains to prove sub-exponential bounds for the complement of $E_{r,u}^{(1)}$. However, by the definition of a Poisson line process the number of lines with the properties described in $E_{r,u}^{(1)}$ is Poisson-distributed with parameter $\frac{\lambda}{12}\sqrt{ur}$. In particular, $\mathbb{P}(E_{r,u}^{(1)}) = 1 - \exp(-\frac{\lambda}{12}\sqrt{ur})$.

4. Proof of Theorem 1

To prove Theorem 1, we proceed in three steps, where we use the general method of global and local paths that has already been successfully applied in literature, see [1, 2, 4, 12, 34]. First, in Section 4.1, we discretise \mathbb{R}^d into boxes, allowing us to use results from percolation theory on lattices. Next, in Section 4.2 we explain how to construct a global path, i.e. a path that is used to move from a point on G close to o to a point on G close to re_1 . Finally, in Section 4.3, we provide a construction for local paths that are used to connect $q(o)$ and $q(re_1)$ to the global path constructed in the previous step.

4.1. Discretisation of the Euclidean space into boxes

In order to prove that the probability $\mathbb{P}(\ell(o, re_1) \geq ur)$ decreases as stated in (4) if $ur \rightarrow \infty$, it suffices to show that with high probability we can construct *some* path of length at most ur connecting $q(o)$ and $q(re_1)$ (because then $\ell(o, re_1) \leq ur$). Here, we recall that $q(o)$ and $q(re_1)$ denote the closest points on the graph G to the origin and to re_1 , respectively. To construct such a path, we decompose the Euclidean space \mathbb{R}^d into congruent d -dimensional sub-cubes with a certain side length $L > 0$. In particular, our goal is to move only along cubes for which the total length of the random geometric graph is bounded from above and for which it is possible to directly pass to neighbouring cubes along the random geometric graph. We call these cubes L -good cubes/sites in the following, other cubes are called L -bad cubes/sites, see also Definition 1 below. Loosely speaking, L -good cubes describe sub-regions of \mathbb{R}^d , where the graph G has good properties, which are closely related to the growth, stability and connectivity conditions (G1)-(G3) introduced in Section 2.1.

Like in [4], we will show that this allows us to construct efficient paths inside connected components of L -good cubes and also that non-percolation of L -bad cubes occurs for all sufficiently large $L > 0$. For illustrations of the situation in two configurations, see Figure 3, where L -bad cubes are shaded. For simplicity, only the left figure shows the underlying graph.

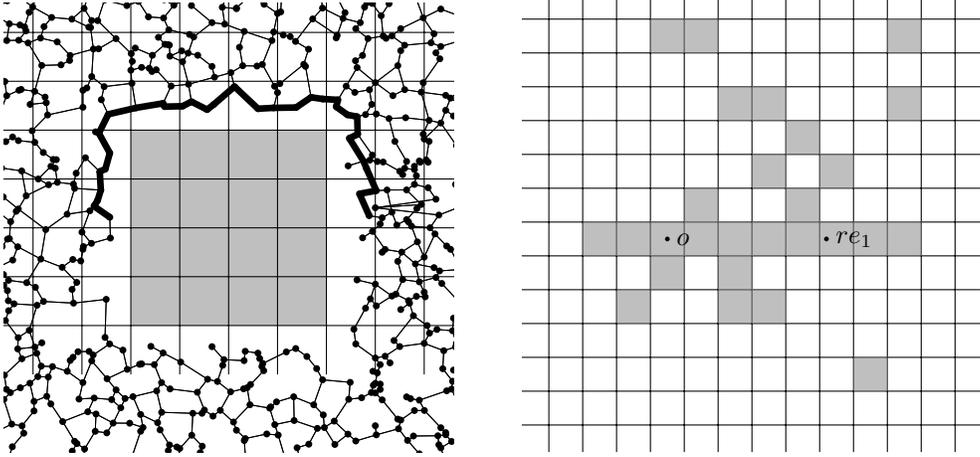


FIGURE 3: A path (thick) avoiding L -bad cubes (left) and L -bad connected component containing o and re_1 (right)

More precisely, we introduce the following definition.

Definition 1. Let $L > 0$, $z \in \mathbb{Z}^d$ and put $c_L = (5L)^d L$. Furthermore, let $b : \mathbb{N} \rightarrow \mathbb{Z}_{+, \infty}$ be the function considered in condition (G2) of Section 2.1. A site $z \in \mathbb{Z}^d$ is said to be L -good if the following items are satisfied:

- (i) $q(x) \in B_{L/4}(x)$ for all $x \in \mathbb{Q}^d \cap Q_L(Lz)$ and $\nu_1(G \cap Q_{5L}(Lz)) \leq c_L$,
- (ii) $b((X - z') \cap Q_{L/2}(o)) \leq L/2$ for all $z' \in \mathbb{Z}^d \cap Q_{5L+1}(Lz)$,
- (iii) $G \cap Q_{3L}(Lz)$ is contained in a connected component of $G \cap Q_{5L}(Lz)$.

For given $L > 0$, we consider the site percolation model $\{Y_z\}_{z \in \mathbb{Z}^d}$ of L -good sites, where for $z \in \mathbb{Z}^d$ the $\{0, 1\}$ -valued random variable Y_z takes the value 1 if and only if z forms an L -good site. Observe that (due to item (ii)) there exists $m \geq 1$ such that for all sufficiently large $L > 0$ the percolation process defined above is m -dependent. Furthermore, the following useful results hold, where we say that a subset of \mathbb{Z}^d is $*$ -connected if it is a connected set in graph on \mathbb{Z}^d with edges given by $\{\{x, y\} \subset \mathbb{Z}^d : |x - y|_\infty \leq 1\}$.

Lemma 12. Let $\Lambda \subset \mathbb{Z}^d$ be a finite and $*$ -connected set of L -good sites. Then for all $z, z' \in \Lambda$ and all $\eta \in G \cap Q_{3L}(Lz)$, $\eta' \in G \cap Q_{3L}(Lz')$ the points η, η' can be connected by a path in $G \cap (L\Lambda \oplus Q_{5L}(o))$ satisfying $\ell(\eta, \eta') \leq (\#\Lambda + 1)c_L$.

Proof. Put $z = z_0$, $z' = z_k$ and let $\gamma = \langle z_0, z_1, \dots, z_k \rangle \subset \Lambda$ be a self-avoiding path of $*$ -connected vertices connecting z and z' . Geometrically, the path γ corresponds to a sequence of vertex-adjacent cubes $Q_L(Lz_0), Q_L(Lz_1), \dots, Q_L(Lz_k)$. By condition (i) of Definition 1, we have $q(Lz_i) \in G \cap Q_L(Lz_i)$ for all $i \in \{0, \dots, k\}$. Furthermore, by condition (iii), we conclude that $q(Lz_i)$ and $q(Lz_{i+1})$ can be connected by a path in $G \cap Q_{5L}(Lz_i)$. By the same reasoning, we can find corresponding paths from η to $q(Lz_0)$ and from η' to $q(Lz_k)$. Finally, using condition (i), the assertion follows.

Lemma 13. It holds that $\lim_{L \rightarrow \infty} \mathbb{P}(o \text{ is } L\text{-good}) = 1$.

Proof. The growth and stability conditions (G1) and (G2) of Section 2.1 immediately imply conditions (i) and (ii) in Definition 1 of L -goodness. To deal with condition (iii) subdivide $Q_{3L}(o)$ into $k = 6^d$ congruent sub-cubes $Q_{L,1}, \dots, Q_{L,k}$ of side length $L/2$. The connectivity condition (G3) introduced in Section 2.1 implies that if $Q_{L,i}$ and $Q_{L,j}$ are neighbouring sub-cubes, then $G \cap Q_{L,i}$ and $G \cap Q_{L,j}$ are contained in the same connected component of $G \cap Q_{5L}(o)$ whp. Since the growth condition (G1) implies that $G \cap Q_{L,i} \neq \emptyset$ for all $i \in \{1, \dots, k\}$ whp, this observation completes the proof.

Using m -dependence in conjunction with Lemma 13 and stationarity allows us to apply [20, Theorem 0.0]. This means that the family of L -bad sites can be dominated from above by a Bernoulli site percolation model with arbitrarily small marginal probability provided that L is chosen sufficiently large. In particular, we henceforth fix a value of L such that in the dominating Bernoulli site percolation model the size of the $*$ -connected closed component at the origin (also called *cluster size*) admits a finite exponential moment.

4.2. Construction of global paths

In this section we elaborate on how to construct an efficient global path, i.e. a path that is used to move from a point on G not too far from o to a point on G not too far from re_1 . This is done by searching L -good cubes close to o and re_1 that are contained in a set of L -good sites surrounding the L -bad connected components intersecting some cube between o and re_1 .

For every finite set of sites $\Lambda \subset \mathbb{Z}^d$ we can decompose its complement Λ^c into finitely many connected components, i.e., $\Lambda^c = \Lambda_1^c \cup \dots \cup \Lambda_k^c$. Observe that precisely one of these components, say Λ_1^c , is infinite. Furthermore, we define the *external boundary* of Λ as

$$\partial^{\text{ext}} \Lambda = \{z \in \Lambda_1^c : |z - z'|_1 = 1 \text{ for some } z' \in \Lambda\},$$

see Figure 4. Recall from [28, Lemma 2.1] that the external boundary of any $*$ -connected set is again $*$ -connected.

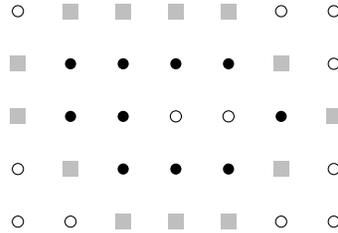


FIGURE 4: Gray squares form external boundary of the set of (filled) black disks

If we consider the site percolation model introduced in Section 4.1, then for any $z \in \mathbb{Z}^d$ we denote by \mathbf{C}_z the $*$ -connected L -bad component at z . Furthermore, for $n \geq 0$ we define $V_n = \partial^{\text{ext}} \left(\bigcup_{i=0}^{n-1} (\mathbf{C}_{ie_1} \cup \{ie_1\}) \right)$ as well as $z_{1,n} = \sup_{k \leq 0} \{ke_1 \in V_n\}$ and $z_{2,n} = \inf_{k \geq n} \{ke_1 \in V_n\}$. Note that $z_{1,n}$ and $z_{2,n}$ are contained in the same $*$ -connected component of L -good sites, see Figure 5, left.

First, we provide an upper bound on the length of the shortest path connecting $q(Lz_{1,n})$ and $q(Lz_{2,n})$.

Lemma 14. *There exists $u_1 \geq 1$ with*

$$\liminf_{\substack{un \rightarrow \infty \\ u \geq u_1, n \geq 1}} \frac{-\log \mathbb{P}(\ell(Lz_{1,n}, Lz_{2,n}) \geq un)}{un} > 0.$$

Proof. First, Lemma 12 implies that $\ell(Lz_{1,n}, Lz_{2,n}) \leq c_L(\#V_n + 1)$ for all $n \geq 1$. Furthermore, there exists $c > 0$ with $\#V_n + 1 \leq c(n + \#A)$, where $A = \bigcup_{i=0}^{n-1} \mathbf{C}_{ie_1}$ denotes the union of the $*$ -connected L -bad components at ie_1 for $i \in \{0, \dots, n-1\}$. In particular,

$$\mathbb{P}(\ell(Lz_{1,n}, Lz_{2,n}) \geq un) \leq \mathbb{P}(n + \#A \geq un/(cc_L)).$$

Recall that the percolation process of L -bad sites can be dominated from above by a sub-critical Bernoulli site percolation process, whose cluster size admits a finite exponential moment, see the remark at the end of Section 4.1. Furthermore, if we consider the union of the closed connected components at the sites ie_1 for $i \in \{0, \dots, n-1\}$, then it has been shown in [11, Lemma 2.3] that the size of this union is dominated from above by $\sum_{i=0}^{n-1} D_i$, where $\{D_i\}_{0 \leq i \leq n-1}$ is a family of i.i.d random variables whose marginal distributions coincide with the distribution of the cluster size. By the choice of L , we have $\exp(a) = \mathbb{E} \exp(h(D_1 + 1)) < \infty$ for some $h > 0$. In particular, for all $u \geq 2acc_L/h$ the Markov inequality yields

$$\mathbb{P}(n + \#A \geq un/(cc_L)) \leq \mathbb{P}\left(\sum_{i=0}^{n-1} (D_i + 1) \geq un/(cc_L)\right) \leq \exp(n(a - uh/(cc_L))).$$

Since the latter expression is at most $\exp(-nuh/(2cc_L))$, this completes the proof.

4.3. Construction of local paths

Similar to the approach considered in [1], to prove Theorem 1 we need the existence of suitable local paths in addition to the global paths constructed in Section 4.2, see Figure 5, right.

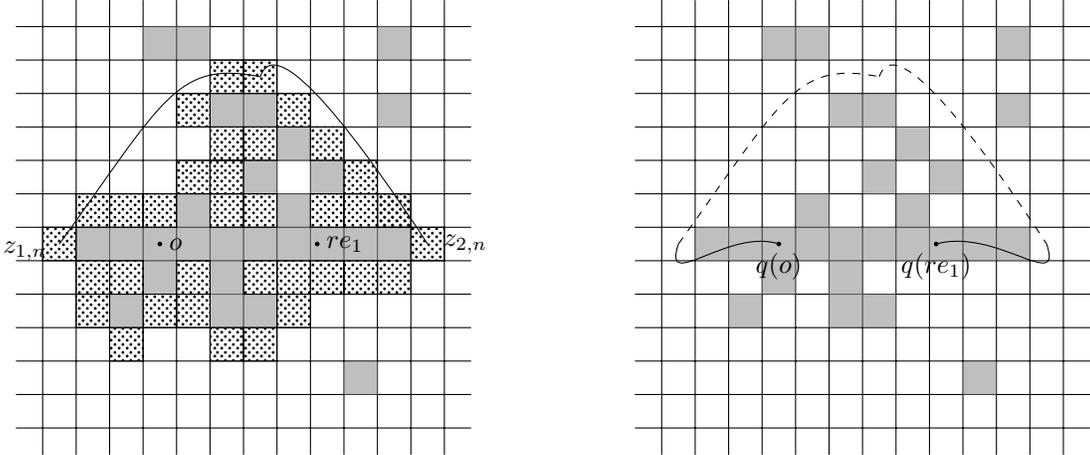


FIGURE 5: Global path and the set V_n (dotted pattern, left) and local path (solid) connecting $q(o)$ resp. $q(re_1)$ to the global path (dashed, right)

The goal of this subsection is to provide the following bounds on the lengths of such local paths.

Lemma 15. *For $r \in \mathbb{R}$ let $n(r) \in \mathbb{Z}$ be the uniquely determined integer n satisfying $-L/2 < L(n-1) - r \leq L/2$. Then, there exist $u_2, u_3 \geq 1$ such that*

$$\liminf_{\substack{ur \rightarrow \infty \\ u \geq u_2, r \geq 1}} \frac{\log(-\log \mathbb{P}(\ell(o, Lz_{1, n(r)}) > ur))}{\log(ur)} > 0, \quad (7)$$

and

$$\liminf_{\substack{ur \rightarrow \infty \\ u \geq u_3, r \geq 1}} \frac{\log(-\log \mathbb{P}(\ell(Lz_{2, n(r)}, re_1) > ur))}{\log(ur)} > 0. \quad (8)$$

Before we begin with the proof of Lemma 15, we extend the definition of V_n introduced in Section 4.2 to negative values of n in a natural way. For $n \leq -1$ and $\Lambda = \bigcup_{i=n+1}^0 \mathbf{C}_{ie_1} \cup \{ie_1\}$ write $V_n = \partial^{\text{ext}} \Lambda$ and $A_n = \mathbb{Z}^d \setminus \Lambda_1^c$, where we recall that Λ_1^c denotes the uniquely determined infinite component of the complement of $\Lambda \subset \mathbb{Z}^d$. The idea is to consider the external boundary $V_{z_{1, n(r)}}$ of the union of L -bad components intersecting

one of the sites $o, -e_1, \dots, (z_{1,n(r)} + 1)e_1$, i.e., $V_{z_{1,n(r)}} = \partial^{\text{ext}}(\bigcup_{i=z_{1,n(r)}+1}^0 (\mathbf{C}_{ie_1} \cup \{ie_1\}))$. We first show in Lemma 16 that any two paths starting from the domain surrounded by this external boundary intersect $V_{z_{1,n(r)}}$ in a particularly nice way that allows us to efficiently join these two paths together along the external boundary. In a second step, see Lemma 17 below, we derive for suitable values of r an upper bound on $\#V_{-n(r)}$, which holds whp.

Lemma 16. *The points $q(o)$ and $q(Lz_{1,n(r)})$ are connected by a path in $G \cap ((LA_{z_{1,n(r)}} \cup LV_{z_{1,n(r)}}) \oplus Q_{5L}(o))$.*

Proof. As G is connected and stationary, there exists a path γ in G starting at $q(o)$ and leaving $(LA_{z_{1,n(r)}} \cup LV_{z_{1,n(r)}}) \oplus Q_{3L}(o)$. Choose $z_0 \in V_{z_{1,n(r)}}$ such that $Lz_0 \oplus Q_{3L}(o)$ is the first cube of the form $\{Lz \oplus Q_{3L}(o)\}_{z \in V_{z_{1,n(r)}}$ that is intersected by γ . Furthermore, we write $\eta \in G \cap (Lz_0 \oplus Q_{3L}(o))$ for the first intersection point of γ and $Lz_0 \oplus Q_{3L}(o)$. Similarly, we can construct analogous objects γ', z'_0 and η' which are obtained when starting from $q(Lz_{1,n(r)})$. Since $V_{z_{1,n(r)}}$ is a $*$ -connected set of L -good sites, we conclude from Lemma 12 that η and η' can be joined by a path inside $LV_{z_{1,n(r)}} \oplus Q_{5L}(o)$.

Lemma 17. *For each $\beta > 0$ there exists $u_4 = u_4(\beta) > 0$ with*

$$\liminf_{\substack{ur \rightarrow \infty \\ u \geq u_4, r \geq 1}} \frac{-\log \mathbb{P}(\#V_{-n(u^\beta r^{2\beta})} > u^{2\beta} r^{2\beta})}{u^{2\beta} r^{2\beta}} > 0.$$

Proof. We can proceed similarly as in the proof of Lemma 14. In particular, there exist $u_4, c_1 \geq 1$ such that for all $u \geq u_4$ and $r \geq 1$ we have $\mathbb{P}(\#V_{-n(u^\beta r^{2\beta})} > n(u^\beta r^{2\beta})u^\beta) \leq \exp(-c_1 n(u^\beta r^{2\beta})u^\beta)$. Furthermore, there exist constants $c_2(L), c_3(L) > 0$ such that for all $u \geq u_4$ and $r \geq 1$ we have $c_2(L)u^{2\beta} r^{2\beta} \leq n(u^\beta r^{2\beta})u^\beta \leq c_3(L)u^{2\beta} r^{2\beta}$, which proves the claim.

Finally, we show that $|z_{1,n(r)}|$ is rather small whp.

Lemma 18. *It holds that*

$$\limsup_{a \rightarrow \infty} \sup_{r \geq 1} \frac{1}{a} \log \mathbb{P}(z_{1,n(r)} < -a) < 0.$$

Proof. Let $a > 0$ and note that if $z_{1,n(r)} < -a$, then there exists $k \geq 0$ such that \mathbf{C}_{ke_1} has diameter larger than $k + a$. As discussed in Section 4.1, we choose L sufficiently large so that this diameter has an exponentially bounded tail. In particular, there exists a constant $c > 0$ with

$$\mathbb{P}(z_{1,n(r)} < -a) \leq \sum_{k=0}^{\infty} \mathbb{P}(\text{diam}(\mathbf{C}_{ke_1}) > k + a) \leq \sum_{k=0}^{\infty} \exp(-c(k + a)) \leq (1 - \exp(-c))^{-1} \exp(-ca).$$

Proof of Lemma 15. Using the notation $k = n(u^{1/(6d+12)} r^{1/(3d+6)})$, by means of Lemma 16 we get that

$$\begin{aligned} \mathbb{P}(\ell(o, Lz_{1,n(r)}) > ur) &\leq \mathbb{P}(\nu_1(G \cap ((LA_{z_{1,n(r)}} \cup LV_{z_{1,n(r)}}) \oplus Q_{5L}(o))) > ur) \\ &\leq \mathbb{P}(z_{1,n(r)} < -k) + \mathbb{P}(\nu_1(G \cap ((LA_{-k} \cup LV_{-k}) \oplus Q_{5L}(o))) > ur). \end{aligned}$$

Observe that by the discrete isoperimetric inequality (see e.g. [11]), $\#V_{-k}$ is at least $d^{-1}(\#A_{-k})^{(d-1)/d}$. In particular, if $t > 0$ is sufficiently large and $\#V_{-k} \leq t$, then $A_{-k} \cup V_{-k} \subset Q_{t^3}(o)$. Hence,

$$\begin{aligned} \mathbb{P}(\ell(o, Lz_{1,n(r)}) > ur) &\leq \mathbb{P}(z_{1,n(r)} < -k) + \mathbb{P}(\#V_{-k} > t) + \mathbb{P}(\nu_1(G \cap Q_{L^3 t^3 + 5L}(o)) > ur) \\ &= \mathbb{P}(z_{1,n(r)} < -k) + \mathbb{P}(\#V_{-k} > t) + \mathbb{P}(\nu_1(G \cap Q_{L^3 t^3 + 5L}(o)) > t^{3d+6}), \end{aligned}$$

where $t = (ur)^{1/(3d+6)}$. Applying the sub-exponential bounds of Lemmas 17 and 18, condition (G1) therefore yields (7). The second assertion of Lemma 15 can be deduced by very similar arguments.

4.4. Combining paths

Finally, we patch together the global and local paths constructed in Sections 4.2 and 4.3, respectively. For all $r \geq 1$ and $u \geq u_0 = 3 \max\{u_1, u_2, u_3\}$ the probability $\mathbb{P}(\ell(o, re_1) > ur)$ is at most

$$\mathbb{P}(\ell(o, Lz_{1,n(r)}e_1) > ur/3) + \mathbb{P}(\ell(Lz_{1,n(r)}e_1, Lz_{2,n(r)}e_1) > ur/3) + \mathbb{P}(\ell(Lz_{2,n(r)}e_1, re_1) > ur/3).$$

The first and third expressions on the right-hand side of this inequality exhibit sub-exponential decay by Lemma 15 (local paths), whereas the second expression exhibits exponential decay by Lemma 14 (global paths). In this way, we can deduce the desired sub-exponential bound stated in Theorem 1.

5. Proofs of Theorems 2 and 3

In this section, we provide proofs of Theorems 2 and 3, which can be seen as applications of Theorem 1.

5.1. Shape theorem

Recall that Theorem 2 can be considered as a shape theorem (in the sense of [18, Theorem 1.7]) for Euclidean first-passage percolation on random geometric graphs. Let G be a stationary, ergodic and isotropic random geometric graph in \mathbb{R}^d for which (4) holds and which satisfies conditions (G1) and (G3). First we derive the following preliminary results stated in Lemmas 19–21 below.

Lemma 19. *Let $\xi \geq 1$ be an arbitrary fixed number. Then*

$$\mathbb{P}(B_{(1-\varepsilon)r}(o) \subset B_{\xi r}^G(o) \subset B_{(1+\varepsilon)r}(o) \text{ for all sufficiently large } r > 0) = 1 \quad (9)$$

for all $\varepsilon > 0$ if and only if for all $\varepsilon > 0$ it holds that

$$\mathbb{P}((\xi - \varepsilon)|x| \leq \ell(o, x) \leq (\xi + \varepsilon)|x| \text{ for all } x \in \mathbb{R}^d \text{ with } |x| \text{ sufficiently large}) = 1. \quad (10)$$

Proof. Let $\varepsilon \in (0, 1)$ be arbitrary and choose a (random) threshold $r_0 > 0$ such that the inclusions in (9) hold for all $r > r_0$ when using $\varepsilon' = \varepsilon/(2\xi)$ instead of ε . Then, for $x \in \mathbb{R}^d$ with $(1 + \varepsilon/\xi)|x| > r_0$ we obtain that $x \in B_{|x|}(o) \subset B_{(1-\varepsilon')(1+\varepsilon/\xi)|x|}(o) \subset B_{\xi(1+\varepsilon/\xi)|x|}^G(o)$, which means that $\ell(o, x) \leq (\xi + \varepsilon)|x|$. Similarly, choosing $r_0 > 0$ as above, the inequality $\ell(o, x) < (\xi - \varepsilon)|x|$ for $|x| > r_0$ would imply that $x \in B_{\xi(1-\varepsilon/\xi)|x|}^G(o) \subset B_{(1+\varepsilon/(2\xi))(1-\varepsilon/\xi)|x|}(o) \subset B_{(1-\varepsilon/(2\xi))|x|}(o)$, which is a contradiction to $|y| < |x|$ for all $y \in B_{(1-\varepsilon/(2\xi))|x|}(o)$. Thus, assuming that (9) holds for all $\varepsilon > 0$, we get that (10) holds for all $\varepsilon > 0$. The reverse implication can be shown similarly.

Lemma 20. *Let $E^{(1)}$ denote the event that $|y_n - q(y_n)|/|y_n| \rightarrow 0$ for all sequences $(y_n)_{n \geq 1}$ with $y_n \in \mathbb{R}^d$ and $|y_n| \rightarrow \infty$. Then, $\mathbb{P}(E^{(1)}) = 1$.*

Proof. Let $z \in \mathbb{Z}^d$ and $\varepsilon \in (0, 1/d)$ be arbitrary. Subdivide the cube $Q_{\varepsilon|z|}(z)$ into $k = (4d+1)^d$ congruent sub-cubes $Q_{z,1}, \dots, Q_{z,k}$ with side length $\varepsilon|z|/(4d+1)$. We say that z is ε -good if each of the k sub-cubes has non-empty intersection with G . It is easy to check that if z is ε -good, then $q(y) \in Q_{(2\sqrt{d}+1)\varepsilon|z|/(4d+1)}(z)$ for all $y \in Q_{\varepsilon|z|/(4d+1)}(z)$. In particular,

$$\frac{|y - q(y)|}{|y|} \leq \frac{\sqrt{d}(2\sqrt{d}+1)\varepsilon \frac{|z|}{4d+1}}{|z| - \sqrt{d}\varepsilon \frac{|z|}{4d+1}} \leq \frac{3d\varepsilon}{4d+1 - \sqrt{d}\varepsilon}.$$

Furthermore, using stationarity, for any $r \geq 1$ we compute

$$\mathbb{P}\left(\bigcup_{z \in \mathbb{Z}^d: |z| \geq r} \{z \text{ is } \varepsilon\text{-bad}\}\right) \leq \sum_{z \in \mathbb{Z}^d: |z| \geq r} \mathbb{P}(z \text{ is } \varepsilon\text{-bad}) \leq (4d+1)^d \sum_{z \in \mathbb{Z}^d: |z| \geq r} \mathbb{P}(Q_{\varepsilon|z|/(4d+1)}(o) \cap G = \emptyset).$$

Now, using condition (G1) in conjunction with the Borel-Cantelli lemma shows that with probability 1 we

only have a finite number of ε -bad lattice points and therefore

$$\limsup_{n \rightarrow \infty} \frac{|y_n - q(y_n)|}{|y_n|} \leq \frac{3d\varepsilon}{4d + 1 - \sqrt{d}\varepsilon}.$$

Since $\varepsilon > 0$ was arbitrary this proves the claim.

Lemma 21. *Let $\alpha > 0$ be arbitrary. If X is a point process satisfying condition (G1), then for $a > 1$ the events $q(o) \in Q_{a^\alpha}(o)$ occur whp.*

Proof. Clearly, $q(o) \in Q_{a^\alpha}(o)$ if $Q_{a^\alpha/\sqrt{d}}(o) \cap G \neq \emptyset$. Hence, the proof is completed by recalling that condition (G1) implies the existence of $c_1, c_2 > 0$ such that $\mathbb{P}(Q_{a^\alpha/\sqrt{d}}(o) \cap G = \emptyset) \leq c_1 \exp(-(a^\alpha/\sqrt{d})^{c_2})$.

Next note the following two results.

Lemma 22. *Let $\tilde{S} \subset \partial B_1(o)$ be a fixed countable subset of the unit sphere in \mathbb{R}^d . Then, there exists $\xi \geq 1$ such that*

$$\mathbb{P}\left(\lim_{n \rightarrow \infty} \ell(o, ns)/n = \xi \text{ for all } s \in \tilde{S}\right) = 1.$$

Proof. By isotropy and the countability assumption, it suffices to prove the assertion for fixed $s = e_1$. It is easy to check that the family of random variables $\{\ell_{k,n} = \ell(ke_1, ne_1)\}_{k,n \geq 0}$ is subadditive. Moreover, it is stationary with respect to the mappings $\{\ell_{k,n}\}_{k,n \geq 0} \mapsto \{\ell_{k+m,n+m}\}_{k,n \geq 0}$, $m \geq 1$. Thus, to apply Kingman's subadditive ergodic theorem [19] it suffices to verify $\mathbb{E}\ell(o, e_1) < \infty$. To prove this claim write $\mathbb{E}\ell(o, e_1) = \int_0^\infty \mathbb{P}(\ell(o, e_1) > \rho) d\rho$. Relation (4) implies that the integrand decays sub-exponentially fast in ρ , so that $\mathbb{E}\ell(o, e_1) < \infty$. Finally, ergodicity of G implies that $\lim_{n \rightarrow \infty} \ell(o, ne_1)/n$ is a.s. constant.

Lemma 23. *Let $\delta \in (0, 1)$ be arbitrary. For $a > 1$ and $\eta \in G \cap Q_{a^\delta}(o)$ denote by $E_{\eta,a}^{(2)}$ the event that $\ell(o, \eta) \leq a^{2d\delta}$. Then, there exists a family of events $(E_a^{(2)})_{a>1}$ such that the occurrence of $E_a^{(2)}$ implies the occurrence of $E_{\eta,a}^{(2)}$ for all $\eta \in G \cap Q_{a^\delta}(o)$ and such that for $a > 1$ the events $E_a^{(2)}$ occur whp.*

Proof. By Lemma 21, we have $q(o) \in Q_{3a^\delta}(o)$ whp and by condition (G3) for any $\eta \in Q_{3a^\delta}(o)$ we know that $q(o)$ and η can be connected by a path in $G \cap Q_{5a^\delta}(o)$ whp. In particular, it suffices to show that for $a > 1$ the events $\nu_1(Q_{5a^\delta}(o) \cap G) \leq a^{2d\delta}$ occur whp. To show this, we may subdivide $Q_{5a^\delta}(o)$ into $k = \lceil 5a^\delta \rceil^d$ congruent sub-cubes of side length at most 1 and apply condition (G1) to obtain that $\nu_1(Q_{5a^\delta}(o) \cap G) \leq ka^\delta \leq a^{2d\delta}$ holds whp.

Finally, we need one further preliminary lemma. A similar result is also the key ingredient in Kesten's original proof, see [18, Lemma 3.6].

Lemma 24. *For $0 < \varepsilon < 1/4$ write $E_\varepsilon^{(3)}$ for the following event. There exists a random $K > 0$ such that $\ell(\eta, \eta') \leq 4u_0 |\eta - \eta'|$ for all $\eta, \eta' \in G$ with $|\eta| \geq K$ and $\varepsilon |\eta|/2 \leq |\eta - \eta'| \leq 2\varepsilon |\eta|$. Then $\mathbb{P}(E_\varepsilon^{(3)}) = 1$.*

Proof. For every $u > 1$ and $z \in \mathbb{Z}^d$ with $|z|$ sufficiently large, we consider the probability

$$\mathbb{P}(\text{there exist } \eta, \eta' \in G \text{ with } \ell(\eta, \eta') \geq u |\eta - \eta'|, \eta \in Q_1(z) \text{ and } \varepsilon |\eta|/2 \leq |\eta - \eta'| \leq 2\varepsilon |\eta|)$$

and, putting $D(z, \varepsilon) = \{z' \in \mathbb{Z}^d : \varepsilon|z|/4 \leq |z - z'| \leq 4\varepsilon|z|\}$, we note that it is at most

$$\begin{aligned} & \sum_{z' \in D(z, \varepsilon)} \mathbb{P}(\text{there exist } \eta, \eta' \in G \text{ with } \ell(\eta, \eta') \geq u|z - z'|/2, \eta \in Q_1(z) \text{ and } \eta' \in Q_1(z')) \\ & \leq \sum_{z' \in D(z, \varepsilon)} \mathbb{P}(\ell(z, z') \geq u|z - z'|/4) \\ & + \sum_{z' \in D(z, \varepsilon)} \mathbb{P}\left(\text{there exists } \eta \in G \cap Q_{|z|^{1/(4d)}}(z) \text{ with } \ell(z, \eta) \geq \sqrt{|z|}\right) \\ & + \sum_{z' \in D(z, \varepsilon)} \mathbb{P}\left(\text{there exists } \eta' \in G \cap Q_{|z|^{1/(4d)}}(z') \text{ with } \ell(z', \eta') \geq \sqrt{|z|}\right). \end{aligned}$$

Choosing $u = 4u_0$, and applying Lemma 23 and Theorem 1 in conjunction with the Borel-Cantelli lemma then completes the proof.

Using these auxiliary results, we may now proceed similarly to [18, Theorem 1.7] to deduce Theorem 2.

Proof of Theorem 2. Let $\varepsilon > 0$ be arbitrary. Our goal is to show that

$$-\varepsilon + \xi \leq \ell(o, y)/|y| \leq \xi + \varepsilon \quad (11)$$

for all $y \in \mathbb{R}^d$ with $|y|$ sufficiently large. We assume that we are given a realisation where the event $E_{m-1}^{(3)}$ in Lemma 24 occurs for all $m \geq 1$ and where additionally the event $E^{(1)}$ of Lemma 20 occurs. For the sake of deriving contradiction, we assume that there exists a sequence y_n with $|y_n| \rightarrow \infty$, $y_n|y_n|^{-1} \rightarrow z \in \partial B_1(o)$ so that (11) is violated for these $y_n \in \mathbb{R}^d$, when ε is replaced by $8u_0\varepsilon$. Since $|q(y_n) - y_n|/|y_n| \rightarrow 0$, we may assume $y_n = q(y_n)$. Now, choose an arbitrary countable dense subset $\tilde{S} \subset \partial B_1(o)$ and an element $s \in \tilde{S}$ such that $\varepsilon \leq |s - z| \leq 5\varepsilon/4$. Then,

$$\left| \frac{\ell(o, y_n)}{|y_n|} - \xi \right| \leq \left| \frac{\ell(o, y_n)}{|y_n|} - \frac{\ell(o, \lfloor |y_n| \rfloor s)}{|y_n|} \right| + \left| \frac{\ell(o, \lfloor |y_n| \rfloor s)}{|y_n|} - \xi \right| \leq \frac{\ell(y_n, \lfloor |y_n| \rfloor s)}{|y_n|} + \left| \frac{\ell(o, \lfloor |y_n| \rfloor s)}{|y_n|} - \xi \right|.$$

By Lemma 22, the second expression tends to 0 as $n \rightarrow \infty$. Thus, it remains to consider the behaviour of the first expression. For simplicity write $k_n = \lfloor |y_n| \rfloor$ and $x_n = q(k_n s)$, so that $\ell(y_n, k_n s) = \ell(y_n, x_n)$. Now,

$$|y_n - x_n| \leq |y_n - k_n z| + k_n |z - s| + |k_n s - x_n| = k_n (|y_n/k_n - z| + |z - s| + |s - x_n/k_n|).$$

By Lemma 20, the third summand is less than $\varepsilon/8$ for all n sufficiently large. Furthermore, by the definition of z , the same holds for the first summand. As the second summand is at most $5\varepsilon/4$, we conclude that $|y_n - x_n| \leq 3k_n\varepsilon/2 \leq 2|y_n|\varepsilon$. Similarly, as $|z - s| > \varepsilon$, one shows that $|y_n - x_n| \geq |y_n|\varepsilon/2$. An application of Lemma 24 thus yields $\ell(y_n, x_n)/|y_n| \leq 4u_0|y_n - x_n|/|y_n| \leq 8u_0\varepsilon$. Since $\varepsilon > 0$ was arbitrary, this completes the proof of Theorem 2.

We conclude this section by showing that if (10) is satisfied for G , then so it is for the Palm version G^* of G with respect to $\nu_1(\cdot \cap G)$.

Proposition 1. *Let G be a stationary and isotropic random geometric graph in \mathbb{R}^d . If (10) is satisfied for G , then it is also satisfied for G^* .*

Proof. For enhanced readability, we write ℓ_G for lengths of shortest paths on G and ℓ_{G^*} for lengths of shortest paths on G^* , respectively. We only prove the statement for the first inequality in (10), the second

one being very similar. First, note that for all $\varepsilon > 0$ the definition of Palm versions yields

$$\begin{aligned} & \mathbb{P}((\xi - \varepsilon) |x| \leq \ell_{G^*}(o, x) \text{ for all } x \in \mathbb{R}^d \text{ with } |x| \text{ sufficiently large}) \\ &= \frac{1}{\gamma} \mathbb{E} \int_{G \cap Q_1(o)} \mathbf{1}_{(\xi - \varepsilon) |x - y| \leq \ell_G(y, x) \text{ for all } x \in \mathbb{R}^d \text{ with } |x - y| \text{ sufficiently large}} dy. \end{aligned}$$

In particular, it suffices to prove that for all $\varepsilon > 0$ there exists a (random) threshold $r_0 > 0$ such that for all $y \in Q_1(o) \cap G$ and all $x \in \mathbb{R}^d$ with $|x - y| \geq r_0$ we have $(\xi - \varepsilon) |x - y| \leq \ell_G(y, x)$. Therefore, let $\varepsilon > 0$ be arbitrary and choose a (random) threshold $r'_0 > 0$ such that the inequalities in (10) hold for G with $\varepsilon/4$ instead of ε and all $x \in \mathbb{R}^d$ with $|x| \geq r'_0$. Then, we choose $r_0 > 0$ sufficiently large such that $r_0 \geq \max\{2\sqrt{d}\xi\varepsilon^{-1}, r'_0 + \sqrt{d}\}$ and $\ell_G(y, o) \leq (r_0 - \sqrt{d})\varepsilon/4$ hold for all $y \in G \cap Q_1(o)$. In particular, for all $y \in Q_1(o) \cap G$ and all $x \in \mathbb{R}^d$ with $|x - y| \geq r_0$ we compute $\ell_G(y, x) \geq \ell_G(o, x) - \ell_G(o, y) \geq (\xi - \varepsilon/4) |x| - \varepsilon |x|/4 \geq (\xi - \varepsilon) |x - y|$. This completes the proof of $(\xi - \varepsilon) |x - y| \leq \ell_G(y, x)$ and the second inequality of (10) can be obtained by a similar reasoning.

5.2. Boundedness of cells

For the convenience of the reader, we recall the statement of Theorem 3. Let G be a stationary and isotropic random geometric graph in \mathbb{R}^2 for which relation (4) holds and which satisfies conditions (G1) and (G3). Then, with probability 1 all cells of G are bounded.

Proof of Theorem 3. For $r > 0$ we write $S_r = \{z \in \mathbb{Z}^d : |z|_\infty = \lceil r \rceil\}$ for the discrete d_∞ -sphere in \mathbb{Z}^d of radius $\lceil r \rceil$ centred at o . Moreover, for $z \in S_r$ we denote by $z^{\text{ccw}} \in \mathbb{Z}^2$ the counter-clockwise successor of z in S_r . We also denote by C_r the event that $q(rz) \in Q_{\sqrt{r}}(rz)$ for all $z \in S_r$ and that $\ell(rz, rz^{\text{ccw}}) \leq 2u_0r$ for all $z \in S_r$. Then, by stationarity, it suffices to prove the a.s. boundedness of the zero-cell of G . Moreover, the occurrence of C_r implies the boundedness of the zero-cell provided that $r > 0$ is sufficiently large. Hence, it suffices to prove that the probability that C_r fails for infinitely many integer values of r is 0. Note that this probability is at most $\sum_{z \in S_r} (\mathbb{P}(q(rz) \notin Q_{\sqrt{r}}(rz)) + \mathbb{P}(\ell(rz, rz^{\text{ccw}}) \geq 2u_0r))$. The sub-exponential decay of this sum follows from Lemma 21 and Theorem 1, so that the proof is completed by an application of the Borel-Cantelli lemma.

6. Proof of Theorem 4

The proof of Theorem 4 is subdivided into several steps. First, we recall from [22, Theorem 6.5] that if Ξ, Ξ_1, Ξ_2, \dots are random closed sets in \mathbb{R}^2 with $\Xi_n \xrightarrow{D} \Xi$, then $\mathbb{P}(\Xi_n \cap K = \emptyset) \rightarrow \mathbb{P}(\Xi \cap K = \emptyset)$ for all compact $K \subset \mathbb{R}^2$ with $\mathbb{P}(\Xi \cap K = \emptyset) = \mathbb{P}(\Xi \cap \text{int } K = \emptyset)$. We begin by considering an elementary convergence property.

Lemma 25. *Let Ξ, Ξ_1, Ξ_2, \dots be random compact convex sets in \mathbb{R}^2 with $\Xi_n \xrightarrow{D} \Xi$. Furthermore, suppose that $o \in \text{int } \Xi$ and $\mathbb{P}(\{\Xi_i = \emptyset\} \cup \{o \in \Xi_i\}) = 1$ for all $i \geq 1$. Then, $\mathbb{P}(\Xi_n \subset \text{int } B) \rightarrow \mathbb{P}(\Xi \subset B)$ for all compact, convex $B \subset \mathbb{R}^2$ with $o \in B$ and $\mathbb{P}(\Xi \subset B) = \mathbb{P}(\Xi \subset \text{int } B)$.*

Proof. Observe that $\Xi \subset B$ if and only if $\Xi \cap (B \oplus \text{int } B_1(o)) \setminus B = \emptyset$ and similarly $\Xi \subset \text{int } B$ if and only if $\Xi \cap (B \oplus B_1(o)) \setminus \text{int } B = \emptyset$. In particular,

$$\lim_{n \rightarrow \infty} \mathbb{P}(\Xi_n \subset \text{int } B) = \lim_{n \rightarrow \infty} \mathbb{P}(\Xi_n \cap (B \oplus B_1(o)) \setminus \text{int } B = \emptyset) = \mathbb{P}(\Xi \cap (B \oplus B_1(o)) \setminus \text{int } B = \emptyset),$$

which completes the proof, since the latter expression equals $\mathbb{P}(\Xi \subset B)$.

Next, we identify the distributional limit of the scaled Voronoi cells $\sqrt{\lambda}\Xi_{0,\lambda}$. In the following, we denote by Ξ_0 the zero-cell of the Voronoi tessellation on $Y \cup \{o\}$, where Y is a homogeneous Poisson point process with intensity $\gamma = \mathbb{E}\nu_1(G \cap Q_1(o))$.

Lemma 26. *As $\lambda \rightarrow 0$ the scaled Voronoi cells $\sqrt{\lambda}\Xi_{0,\lambda}$ converge in distribution to Ξ_0 .*

Proof. First we claim $\sqrt{\lambda}X_\lambda \xrightarrow{D} Y$ as $\lambda \rightarrow 0$. Indeed, observe that for any $\lambda \in (0, 1)$ the point process X_λ can be obtained from X_1 by applying an independent thinning with survival probability λ . In particular, the claim follows from [10, Exercise 11.3.4] or [21, Theorem 7.3.1]. By the continuous mapping theorem it suffices to show that the map which assigns to a point process the zero-cell of its associated Voronoi tessellation has discontinuities only in a null set with respect to the distribution of $Y \cup \{o\}$. So let $\varphi \subset \mathbb{R}^2$ be a locally finite set such that the interior of each of the four quadrants contains at least one point. For such locally finite φ we define $\text{Vor}_0(\varphi)$ to be the unique cell of the Voronoi tessellation induced by $\varphi \cup \{o\}$ that contains the origin. Now let $(\varphi_n)_{n \geq 1}$ be a sequence of locally finite sets with $\varphi_n \rightarrow \varphi$. We make use of the characterisation [10, Theorem A 2.6.II], where it is shown that this convergence is equivalent to $\varphi_n(A) \rightarrow \varphi(A)$ for all $A \in \mathcal{B}_0(\mathbb{R}^2)$ with the property $\varphi(\partial A) = 0$. Our goal is to deduce $\text{Vor}_0(\varphi_n) \rightarrow \text{Vor}_0(\varphi)$. First, choose some fixed $r \geq 4$ such that $B_{r/4}(o)$ contains $\text{Vor}_0(\varphi)$ and such that $\partial B_r(o) \cap \varphi = \emptyset$. Then there exists $k > 0$ with $\varphi_n(B_r(o)) = \varphi(B_r(o)) = k$ for all sufficiently large n . Write $\varphi \cap B_r(o) = \{P_1, \dots, P_k\}$. Furthermore, choose $\varepsilon_0 > 0$ such that $B_{2\varepsilon_0}(P_i) \subset B_r(o)$ for all $i \in \{1, \dots, k\}$ and such that $B_{\varepsilon_0}(P_i) \cap B_{\varepsilon_0}(P_j) = \emptyset$ for all distinct $i, j \in \{1, \dots, k\}$. Then again for all sufficiently large n , we have $\varphi_n(B_{\varepsilon_0}(P_i)) = 1$ for all $i \in \{1, \dots, k\}$ so that for all such n there exist unique $P_1^{(n)}, \dots, P_k^{(n)} \in \varphi_n$ with $|P_i - P_i^{(n)}| \leq \varepsilon_0$ for all $i \in \{1, \dots, k\}$. To prove the convergence $\text{Vor}_0(\varphi_n) \rightarrow \text{Vor}_0(\varphi)$ we use criterion (c) of [30, Theorem 12.2.2]. So let $x \in \text{Vor}_0(\varphi)$ and $\varepsilon \in (0, \varepsilon_0)$ be arbitrary. It is easy to see that there exist $\delta > 0$ and $y_0 \in B_\varepsilon(x)$ with $|y_0 - P_j| \geq |y_0| + 2\delta$ for all $j \in \{1, \dots, k\}$. We prove $B_\varepsilon(x) \cap \text{Vor}_0(\varphi_n) \neq \emptyset$ eventually by showing that for all sufficiently large values of $n \geq 1$ we have $\inf_{P \in \varphi_n} |y_0 - P| \geq |y_0|$. To prove this claim, we distinguish two cases. If $P \in \varphi_n \setminus B_r(o)$, then $|y_0 - P| \geq r/2 \geq |y_0|$. On the other hand, suppose we are given $P = P_j^{(n)}$ for some $j \in \{1, \dots, k\}$. Note that $|P_j - P_j^{(n)}| < \delta$ for all $j \in \{1, \dots, k\}$ provided n is sufficiently large. In particular,

$$|y_0 - P_j^{(n)}| \geq |y_0 - P_j| - |P_j - P_j^{(n)}| \geq |y_0| + \delta.$$

This completes the proof of the first item of condition (c). Next, suppose we are given a sequence $(n_i)_{i \geq 1}$ and $x_{n_i} \in \text{Vor}_0(\varphi_{n_i})$ with $x_{n_i} \rightarrow x \in \mathbb{R}^2$. We want to prove $x \in \text{Vor}_0(\varphi)$. If this claim was false, we could find $\delta > 0$ and $j \in \{1, \dots, k\}$ with $|x| \geq |x - P_j| + \delta$. But this implies $|x_{n_i}| \geq |x_{n_i} - P_j^{(n_i)}| + \delta/2$ for all sufficiently large values of i , thereby contradicting the assumption $x_{n_i} \in \text{Vor}_0(\varphi_{n_i})$.

Next, we note that for small λ and large K the cell $\Xi_{0,\lambda}$ is likely to be contained in $Q_{K/\sqrt{\lambda}}(o)$.

Lemma 27. *It holds that $\lim_{K \rightarrow \infty} \lim_{\lambda \rightarrow 0} \mathbb{P}(\Xi_{0,\lambda} \subset Q_{K/\sqrt{\lambda}}(o)) = 1$.*

Proof. First, observe that $\mathbb{P}(\Xi_{0,\lambda} \subset Q_{K/\sqrt{\lambda}}(o)) = \mathbb{P}(\sqrt{\lambda}\Xi_{0,\lambda} \subset Q_K(o))$ and that Lemma 26 implies the convergence $\sqrt{\lambda}\Xi_{0,\lambda} \xrightarrow{D} \Xi_0$ as $\lambda \rightarrow 0$. Furthermore, it is easy to see that $\mathbb{P}(\Xi_0 \subset Q_K(o)) = \mathbb{P}(\Xi_0 \subset \text{int } Q_K(o))$, so that Lemma 25 yields $\lim_{\lambda \rightarrow 0} \mathbb{P}(\Xi_{0,\lambda} \subset \text{int } Q_{K/\sqrt{\lambda}}(o)) = \mathbb{P}(\Xi_0 \subset Q_K(o))$. We conclude by observing that $\lim_{K \rightarrow \infty} \mathbb{P}(\Xi_0 \subset Q_K(o)) = 1$.

Lemma 28. *Let $\alpha \in (0, 1)$ and $K > 0$ be arbitrary. Then $\lim_{s \rightarrow \infty} \mathbb{P}(\sup_{x \in Q_{Ks}(o)} |x - q(x)| > s^\alpha) = 0$.*

Proof. Subdivide $Q_{Ks}(o)$ into $k = \lceil \sqrt{2}Ks^{1-\alpha} \rceil^2$ congruent sub-squares $Q_{s,1}, \dots, Q_{s,k}$ satisfying $\text{diam}(Q_{s,i}) \leq s^\alpha$ for all $i \in \{1, \dots, k\}$. Then $\mathbb{P}(\sup_{x \in Q_{Ks}(o)} |x - q(x)| > s^\alpha) \leq \sum_{i=1}^k \mathbb{P}(Q_{s,i} \cap G^* = \emptyset)$ which by condition (G1) tends to 0 as $s \rightarrow \infty$.

We write \mathcal{K} for the family of convex compact sets in \mathbb{R}^2 .

Lemma 29. *Let $r > 0$ and A be a convex polygon with no two parallel sides and such that no circle of radius r touches three (or more) sides of A . Then the erosion operation $h : \mathcal{K} \rightarrow \mathcal{K}$, $A' \mapsto h(A') = A' \ominus B_r(o)$ is continuous at A .*

Proof. Suppose $A_n \rightarrow A$ as $n \rightarrow \infty$. To prove the convergence $A_n \ominus B_r(o) \rightarrow A \ominus B_r(o)$ we use criterion (c) of [30, Theorem 12.2.2]. Hence, we first suppose $x \in A \ominus B_r(o)$, i.e. $B_r(x) \subset A$. By assumption $B_r(x)$ is tangent to at most 2 sides of A and we suppose that it is tangent to *exactly* two sides (the other cases are similar, but easier). Write u, v for the two unit vectors pointing from x in the direction of the two tangent

points. Furthermore, define $w = u + v$ (observe that $w \neq 0$ due to the non-parallelity assumption). It is easy to check that for all sufficiently small $\delta > 0$ the ball $B_r(x - \delta w)$ has positive distance, say at least $\varepsilon = \varepsilon(\delta) > 0$, from all sides of A . Denote by $\{P_1, \dots, P_k\}$ the vertices of the polygon A , see Figure 6a. Then by condition (b1) of [30, Theorem 12.2.2] for all sufficiently large $j \geq 1$ we have $A_j \cap \text{int } B_{\varepsilon/2}(P_i) \neq \emptyset$ for all $i \in \{1, \dots, k\}$. Since the convex hull of $\{y_1, \dots, y_k\}$ contains $B_r(x - \delta w)$ for all choices of points $y_i \in \text{int } B_{\varepsilon/2}(P_i)$, we obtain that $B_r(x - \delta w) \subset A_j$. But this is simply a reformulation of $x - \delta w \in A_j \ominus B_r(o)$. Since $\delta > 0$ was arbitrary this proves condition (c1).

To check condition (c2) we start from a given a sequence $(n_i)_{i \geq 1}$ and points $x_{n_i} \in A_{n_i} \ominus B_r(o)$ with $x_{n_i} \rightarrow x$ for some $x \in \mathbb{R}^2$. Our goal is to deduce $B_r(x) \subset A$. Suppose we could find $y \in B_r(x) \setminus A$. Then there exists $\varepsilon > 0$ with $B_\varepsilon(y) \cap A = \emptyset$, see Figure 6b. By criterion (b2) of [30, Theorem 12.2.2], we then also have $B_\varepsilon(y) \cap A_{n_i} = \emptyset$ for all sufficiently large $i \geq 1$. Now choose $y' \in B_\varepsilon(y)$ with $|y' - x| \leq r - \varepsilon$. Then we compute $|y' - x_{n_i}| \leq |y' - x| + |x - x_{n_i}| \leq r - \varepsilon + |x - x_{n_i}|$. In particular, $y' \in B_r(x_{n_i})$ for all sufficiently large values of i thereby contradicting $x_{n_i} \in A_{n_i} \ominus B_r(o)$.

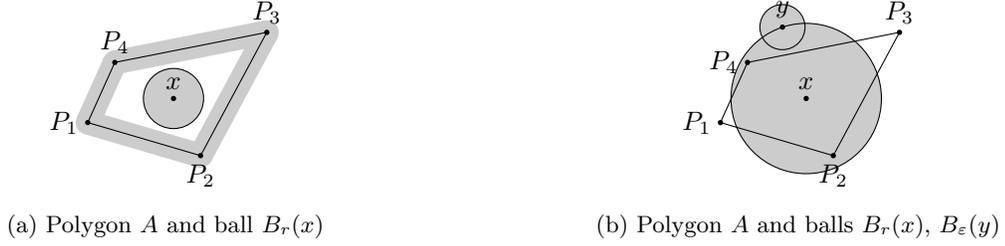


FIGURE 6: Configurations in the proof of Lemma 29

Now we have collected all necessary preliminaries to prove Theorem 4.

Proof of Theorem 4. Let $\delta, \varepsilon \in (0, 1)$ be arbitrary. Using Lemmas 27 and 28, for all sufficiently small $\lambda > 0$ we obtain

$$\mathbb{P}(\sqrt{\lambda}Z(\lambda) \leq x) = \mathbb{P}\left(\max_{P_1 \in \Xi_{0,\lambda} \cap G^*} \ell(o, P_1) \leq x/\sqrt{\lambda}\right) \leq \mathbb{P}\left(\max_{P \in \Xi_{0,\lambda} \ominus B_{\delta/\sqrt{\lambda}}(o)} \ell(o, q(P)) \leq x/\sqrt{\lambda}\right) + \varepsilon,$$

and the last probability is equal to $\mathbb{P}(\Xi_{0,\lambda} \ominus B_{\delta/\sqrt{\lambda}}(o) \subset B_{x/\sqrt{\lambda}}^{G^*}(o)) + \varepsilon$. Furthermore, Theorem 2 yields

$$\begin{aligned} \mathbb{P}(\Xi_{0,\lambda} \ominus B_{\delta/\sqrt{\lambda}}(o) \subset B_{x/\sqrt{\lambda}}^{G^*}(o)) &\leq \mathbb{P}\left(\Xi_{0,\lambda} \ominus B_{\delta/\sqrt{\lambda}}(o) \subset \text{int } B_{(x+\delta)/(\xi\sqrt{\lambda})}(o)\right) + \varepsilon \\ &= \mathbb{P}\left(\sqrt{\lambda}\Xi_{0,\lambda} \ominus B_\delta(o) \subset \text{int } B_{(x+\delta)/\xi}(o)\right) + \varepsilon, \end{aligned}$$

for all sufficiently small $\lambda > 0$. By Lemma 29, we obtain that the operation $\cdot \ominus B_\delta(o)$ is a.s. continuous at Ξ_0 . In particular, from $\sqrt{\lambda}\Xi_{0,\lambda} \xrightarrow{D} \Xi_0$ we deduce $\sqrt{\lambda}\Xi_{0,\lambda} \ominus B_\delta(o) \xrightarrow{D} \Xi_0 \ominus B_\delta(o)$. Using $\mathbb{P}(\Xi_0 \ominus B_\delta(o) \subset B_{(x+\delta)/\xi}(o)) = \mathbb{P}(\Xi_0 \ominus B_\delta(o) \subset \text{int } B_{(x+\delta)/\xi}(o))$ and Lemma 25, we conclude

$$\limsup_{\lambda \rightarrow 0} \mathbb{P}(\sqrt{\lambda}Z(\lambda) \leq x) \leq \mathbb{P}(\Xi_0 \ominus B_\delta(o) \subset B_{(x+\delta)/\xi}(o)) + 2\varepsilon,$$

so that letting $\delta \rightarrow 0$ yields

$$\limsup_{\lambda \rightarrow 0} \mathbb{P}(\sqrt{\lambda}Z(\lambda) \leq x) \leq \mathbb{P}(\text{int } \Xi_0 \subset B_{x/\xi}(o)) + 2\varepsilon \leq \mathbb{P}(\xi R \leq x) + 2\varepsilon.$$

In the next step, we prove a similar inequality in the other direction. Let $\delta, \varepsilon > 0$ be arbitrary. Then, for all

sufficiently small $\lambda > 0$ we obtain

$$\mathbb{P}(\sqrt{\lambda}Z(\lambda) > x) = \mathbb{P}\left(\max_{Q_1 \in \Xi_{0,\lambda} \cap G^*} \ell(o, Q_1) > x/\sqrt{\lambda}\right) \leq \mathbb{P}\left(\max_{Q \in \Xi_{0,\lambda}} \ell(o, q(Q)) > x/\sqrt{\lambda}\right),$$

which equals $\mathbb{P}(\Xi_{0,\lambda} \not\subset B_{x/\sqrt{\lambda}}^{G^*}(o))$. Using Theorem 2 we obtain

$$\mathbb{P}\left(\Xi_{0,\lambda} \not\subset B_{x/\sqrt{\lambda}}^{G^*}(o)\right) \leq \mathbb{P}\left(\Xi_{0,\lambda} \not\subset \text{int } B_{(x-\delta)/(\xi\sqrt{\lambda})}(o)\right) + \varepsilon = \mathbb{P}\left(\sqrt{\lambda}\Xi_{0,\lambda} \not\subset \text{int } B_{(x-\delta)/\xi}(o)\right) + \varepsilon$$

for all sufficiently small $\lambda > 0$. Hence, by $\mathbb{P}(\Xi_0 \subset B_{(x-\delta)/\xi}(o)) = \mathbb{P}(\Xi_0 \subset \text{int } B_{(x-\delta)/\xi}(o))$ and Lemma 25,

$$\limsup_{\lambda \rightarrow \infty} \mathbb{P}(\sqrt{\lambda}Z(\lambda) > x) \leq \mathbb{P}(\Xi_0 \not\subset B_{(x-\delta)/\xi}(o)) + \varepsilon = \mathbb{P}(\xi R > x - \delta) + \varepsilon,$$

so that letting $\delta \rightarrow 0$ yields $\limsup_{\lambda \rightarrow \infty} \mathbb{P}(\sqrt{\lambda}Z(\lambda) > x) \leq \mathbb{P}(\xi R \geq x) + \varepsilon$. As the distribution function of R is continuous, this proves the claim.

Acknowledgements

The authors would like to thank the anonymous referees for their careful reading of the manuscript. Their suggestions and remarks helped to substantially improve the quality of this article. This work was supported by Orange Labs through Research grant No. 46146063-9241. The first author was supported by a research grant from DFG Research Training Group 1100 at Ulm University.

References

- [1] D. J. Aldous. Which connected spatial networks on random points have linear route-lengths? *arXiv preprint arXiv:0911.5296*, 2009.
- [2] D. J. Aldous and W. S. Kendall. Short-length routes in low-cost networks via Poisson line patterns. *Advances in Applied Probability*, 40:1–21, 2008.
- [3] D. J. Aldous and J. Shun. Connected spatial networks over random points and a route-length statistic. *Statistical Science*, 25:275–288, 2010.
- [4] P. Antal and A. Pisztor. On the chemical distance for supercritical Bernoulli percolation. *Annals of Probability*, 24:1036–1048, 1996.
- [5] F. Baccelli, K. Tchoumatchenko, and S. Zuyev. Markov paths on the Poisson-Delaunay graph with applications to routing in mobile networks. *Advances in Applied Probability*, 32:1–18, 2000.
- [6] E. Bertin, J.-M. Billiot, and R. Drouilhet. Continuum percolation in the Gabriel graph. *Advances in Applied Probability*, 34:689–701, 2002.
- [7] J.-M. Billiot, F. Corset, and E. Fontenas. Continuum percolation in the relative neighborhood graph. *arXiv preprint arXiv:1004.5292*, 2010.
- [8] P. Calka. The distributions of the smallest disks containing the Poisson-Voronoi typical cell and the Crofton cell in the plane. *Advances in Applied Probability*, 34:702–717, 2002.
- [9] D. J. Daley and G. Last. Descending chains, the lilypond model, and mutual-nearest-neighbour matching. *Advances in Applied Probability*, 37:604–628, 2005.
- [10] D. J. Daley and D. D. Vere-Jones. *An Introduction to the Theory of Point Processes I/II*. Springer, New York, 2005/2008.
- [11] J.-D. Deuschel and A. Pisztor. Surface order large deviations for high-density percolation. *Probability Theory and Related Fields*, 104:467–482, 1996.

- [12] O. Garet and R. Marchand. Large deviations for the chemical distance in supercritical Bernoulli percolation. *Annals of Probability*, 35:833–866, 2007.
- [13] C. Gloaguen, F. Voss, and V. Schmidt. Parametric distributions of connection lengths for the efficient analysis of fixed access networks. *Annals of Telecommunications*, 66:1–16, 2011.
- [14] J. M. Hammersley and D. J. A. Welsh. First-passage percolation, subadditive processes, stochastic networks, and generalized renewal theory. In J. Neyman and L. M. LeCam, editors, *Proc. Internat. Res. Semin., Statist. Lab., Univ. California, Berkeley, Calif.*, pages 61–110. Springer, 1965.
- [15] C. Hirsch, D. Neuhäuser, and V. Schmidt. Connectivity of random geometric graphs related to minimal spanning forests. *Advances in Applied Probability*, 45:20–36, 2013.
- [16] C. Hirsch, D. Neuhäuser, C. Gloaguen, and V. Schmidt. Asymptotic properties of Euclidean shortest-path trees and applications in telecommunication networks. (Working Paper).
- [17] D. Jeulin. Dead leaves models: from space tessellation to random functions. In D. Jeulin, editor, *Proceedings of the International Symposium on Advances in Theory and Applications of Random Sets (Fontainebleau, 1996)*, pages 137–156. World Scientific Publishing, River Edge, NJ, 1997.
- [18] H. Kesten. Aspects of first passage percolation. In P. L. Hennequin, editor, *École d’été de probabilités de Saint-Flour, XIV—1984*, volume 1180 of *Lecture Notes in Mathematics*, pages 125–264. Springer, Berlin, 1986.
- [19] J. Kingman. Subadditive ergodic theory. *Annals of Probability*, 1:883–899, 1973.
- [20] T. M. Liggett, R. H. Schonmann, and A. M. Stacey. Domination by product measures. *Annals of Probability*, 25:71–95, 1997.
- [21] K. Matthes, J. Kerstan, and J. Mecke. *Infinitely Divisible Point Processes*. J. Wiley & Sons, Chichester, 1978.
- [22] I. Molchanov. *Theory of Random Sets*. Springer, London, 2005.
- [23] J. Møller. Random Johnson-Mehl tessellations. *Advances in Applied Probability*, 24:814–844, 1992.
- [24] D. Neuhäuser, C. Hirsch, C. Gloaguen, and V. Schmidt. A parametric copula approach for modelling shortest-path trees in telecommunication networks. In A. Dudin and K. Turck, editors, *Analytical and Stochastic Modeling Techniques and Applications*, volume 7984 of *Lecture Notes in Computer Science*, pages 324–336. Springer, Berlin, 2013.
- [25] D. Neuhäuser, C. Hirsch, C. Gloaguen, and V. Schmidt. On the distribution of typical shortest-path lengths in connected random geometric graphs. *Queueing Systems*, 71:199–220, 2012.
- [26] M. Penrose. *Random Geometric Graphs*. Oxford University Press, Oxford, 2003.
- [27] L. Pimentel. Asymptotics for first-passage times on Delaunay triangulations. *Combinatorics, Probability and Computing*, 20:435–453, 2011.
- [28] A. Pisztora. Surface order large deviations for Ising, Potts and percolation models. *Probability Theory and Related Fields*, 104:427–466, 1996.
- [29] A. Rousselle. Recurrence or transience of random walks on random graphs generated by point processes in \mathbb{R}^d . *arXiv preprint arXiv:1305.4878*, 2013.
- [30] R. Schneider and W. Weil. *Stochastic and Integral Geometry*. Springer, Berlin, 2008.

- [31] M. Q. Vahidi-Asl and J. C. Wierman. First-passage percolation on the Voronoi tessellation and Delaunay triangulation. In M. Karoński, J. Jaworski, and A. Ruciński, editors, *Random Graphs '87*, pages 341–359, Chichester, 1990. J. Wiley & Sons.
- [32] M. Q. Vahidi-Asl and J. C. Wierman. A shape result for first-passage percolation on the Voronoi tessellation and Delaunay triangulation. In *Random graphs, Vol. 2 (Poznań, 1989)*, pages 247–262. J. Wiley & Sons, New York, 1992.
- [33] F. Voss, C. Gloaguen, and V. Schmidt. Capacity distributions in spatial stochastic models for telecommunication networks. *Image Analysis & Stereology*, 28:155–163, 2009.
- [34] C.-L. Yao, G. Chen, and T.-D. Guo. Large deviations for the graph distance in supercritical continuum percolation. *Journal of Applied Probability*, 48:154–172, 2011.