

Optimal geometry of transportation networks

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Motivated by the shape of transportation networks such as subways, we consider a distribution of points in the plane and ask for the network G of given length L that is optimal in a certain sense. In the general model, the optimality criterion is to minimize the average (over pairs of points chosen independently from the distribution) time to travel between the points, where a travel path consists of any line segments in the plane traversed at slow speed and any route within the subway network traversed at a faster speed. Of major interest is how the shape of the optimal network changes as L increases. We first study the simplest variant of this problem where the optimization criterion is to minimize the average distance from a point to the network, and we provide some general arguments about the optimal networks. As a second variant we consider the optimal network that minimizes the average travel time to a central destination, and we discuss both analytically and numerically some simple shapes such as the star network, the ring, or combinations of both these elements. Finally, we discuss numerically the general model where the network minimizes the average time between all pairs of points. For this case, we propose a scaling form for the average time that we verify numerically. We also show that in the medium-length regime, as L increases, resources go preferentially to radial branches and that there is a sharp transition at a value L_c where a loop appears.

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I. INTRODUCTION

Transportation networks evolve in time and their structure has been studied in many contexts from street networks to railways and subways [1–4]. The evolution of transportation networks is also relevant in biological cases such as the growth of slime mould [5] or for social insects [6–9]. The specific case of subways is particularly interesting (for network analysis of subways, see for example [2,10–14]). In most very large cities, a subway system has been built and later enlarged [2], with current total lengths L varying from a few kilometers to a few hundred kilometers. We observe that the length of subway networks is distributed over a broad range [see Fig. 1 (top)]. Fig. 1 (bottom) also shows the total length versus the first construction date for most subway networks worldwide (the data is from various sources, see [14] and references therein): the oldest networks are mostly European and the largest and more recent ones can be found in Asia.

Concerning the geometry of these networks, as L increases we observe more complex shapes and an increase in the number of lines (see Fig. 2 and also Ref. [15]). Usually for small subways (L of order a couple of 10 kms) we observe a single line or a simple tree (e.g., a single line in the case of Baltimore, Haifa, Helsinki, Hiroshima, Miami, Mumbai, Xiamen, ...; or many radial lines such as in Atlanta, Bangalore, Incheon, Kyoto, Philadelphia, Rome, Sendai, Warsaw, Boston, Budapest, Buenos Aires, Chicago, Daegu, Kiev, Los Angeles, Sapporo,

Tehran, Vancouver, Washington DC). For larger L (of order 100 kms), we typically observe the appearance of a loop line, either in the form of a single ring (e.g., Glasgow) or multiple lines with connection stations (Athens, Budapest, Lisbon, Munich, Prague, São Paulo, St. Petersburg, Cairo, Chennai, Lille, Marseille, Montreal, Nuremberg, Qingdao, Toronto). For larger networks (L over 200 kms) we observe in general some more complex topological structure (Berlin, Chongqing, Delhi, Guangzhou, Hong Kong, Mexico City, Milan, Nanjing, New York, Osaka, Paris, Shenzhen, Taipei). For the largest networks, convergence to a structure with a well-connected central core and branches reaching out to suburbs has been observed [2].

In this paper we investigate the optimal structure of transportation networks, as a function of length L , for several related notions of *optimal* involving minimizing travel time. Real-world subway networks have developed under many other factors, of course, rather than resulting from the optimization of some simple quantity, but optimal structures provide interesting benchmarks for comparison with real-world networks.

There has been extensive study of optimal networks over a given set of nodes (such as the minimum spanning tree [16] or other optimal trees [17]). Some such problems allow extra chosen nodes, for example, the Steiner tree problem [18], or geometric location problems in which n given demand points are to be matched with p chosen supply points [19]. At another extreme is the much-studied Monge-Kantorovich mass transportation problem [20], involving matching points from one distribution with points from another distribution. Our setting is fundamentally different, in that what we are

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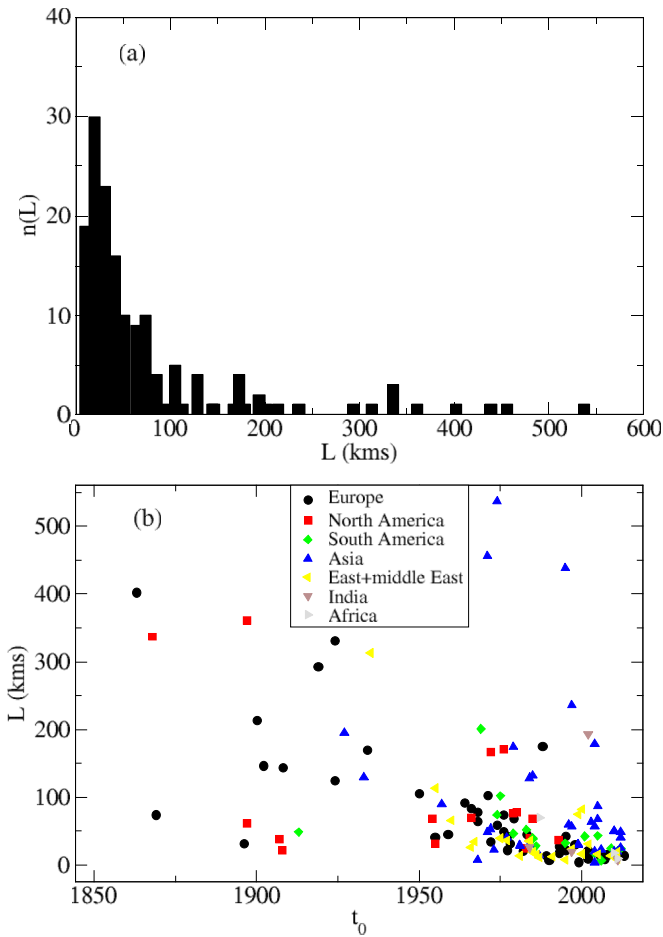


FIG. 1. (a) Histogram of the total length L of subway networks. (b) Total length of the network versus first construction date t_0 . We grouped the networks according to broad regions.

given is just the density of start/end points on the plane. A network is intrinsically one-dimensional, in the sense of being a collection of (maybe curved) lines embedded in the plane. In a sense we are studying a coupling between a given distribution over points in the continuum and a network of our choice constrained only by length and connectedness. Some

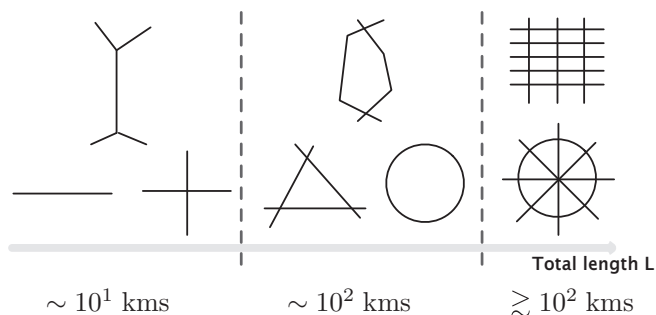


FIG. 2. Typical observed shapes when the length L increases. For small L we observe a line or a simple tree. For larger L we observe the appearance of a loop and for much larger L more complex shapes including a lattice like network or a superimposition of a ring and radial lines.

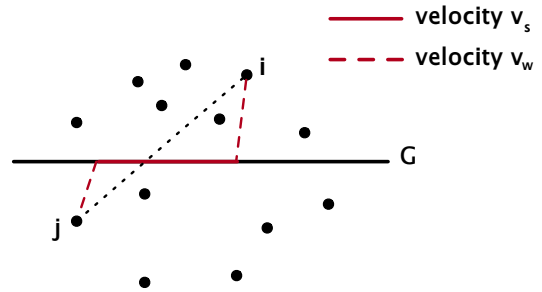


FIG. 3. Definition of the model. Residences or workplaces are represented by points. The graph G represents the subway and we look for the quickest path that connects any pair of nodes. We have to compare the direct path (dotted line) with the “multimodal” path (dashed and solid red lines) that combines both walking and using the subway.

simpler problems of this type have been addressed previously. For instance, the problem of the quickest access between an area and a given point was discussed in Refs. [21,22]. More recently, the impact of the shape of the city and a single subway line was discussed in Ref. [23]. Algorithmic aspects of network design questions similar to ours have been studied within computational geometry (e.g., Ref. [24] chapter 9) and “location science” (e.g., Ref. [25] and references therein). But our specific question—optimal network topologies as a function of population distribution and network length—has apparently not been explicitly addressed.

II. THE MODEL AND THE MAIN QUESTION

Here we define precisely the general model we have in mind, and the three different variants that we will in fact study. Our model makes sense for an arbitrary “population density” $\rho(\cdot)$ on the plane, but we will study mostly the isotropic (rotation-invariant around the origin) case, in particular, the (standard) Gaussian density,

$$\rho(x, y) = (2\pi)^{-1} \exp(-r^2/2), \quad r^2 = x^2 + y^2,$$

and the uniform distribution on a disk. The population density is of individuals who wish to reach as quickly as possible other points in the system (for simplicity we do not distinguish densities of residences and workplaces, for instance). Continuing with the subway interpretation, we assume that one can move anywhere in the plane at speed 1, and one can move within the network at speed $S > 1$ (this quantity can therefore be seen as the ratio $S = v_s/v_w$ between subway and walking velocities, see Fig. 3). Note that we envisage each position on the network as a “station” where the subway is accessible—the relative efficiency of two networks would be little affected by the incorporation of discrete stations into a model. The problem that we consider is the following one. For any pair of points (such as i and j in Fig. 3), we look for the quickest path connecting them. This path either connects directly the points (at walking speed v_w) or uses the graph. More generally, for any pair of points (z_1, z_2) in the plane, there is a minimum (over all possible routes) time $\tau(z_1, z_2)$ to

journey from z_1 to z_2 , and so the average journey time is

$$\bar{\tau} = \iint \tau(z_1, z_2) \rho(z_1) \rho(z_2) dz_1 dz_2.$$

This depends on the network and we consider here graphs of total length L defined as the sum of the length of all edges (note that for the gaussian disorder, the length is counted in unit of its standard deviation σ). For a given L there is some optimal network which will also depend on the speed ratio S and on the density ρ . We study the shapes and average journey times for such optimal networks.

This “general model” is very simplistic—as a next step, a companion paper [27] studies an extended model including a waiting time W whenever we take the subway or connect from one line to another—but nevertheless seems analytically intractable. So in fact we will consider three simpler variants.

First, we will consider the problem of minimizing the average (over starting points from the given distribution) distance to the network, that is to the closest point in the network. Note here that we don’t compute the average time between all pairs of points but just consider the access time to the network from each point. The second variant that we consider is the problem of minimizing the journey time from the points to a single destination, which we may take to be the origin O . In the third variant, we engage the general issue of routes between arbitrary points which typically (but not always) involve entering and exiting the subway network, but now require these entrances and exits to be the closest positions to the starting and ending points, rather than the time-minimizing positions.

Except in asymptotic results [e.g., Eq. (4)] we do not have exact formulas involving optimal networks. Instead we consider a range of simple network shapes, allowing us to investigate the possible shape of optimal networks.

III. A FIRST SIMPLIFICATION: OPTIMAL PLACEMENT

Here we consider the simplest variant, in which we seek the network (of given length L) that minimizes the average distance from a point to the network. This is almost the same as the $S = \infty$ case of the general model, because the journey time between two points would be the sum of the two distances to the network, except that in the general model the shortest route might not use the subway network at all. Intuitively an optimal network must come close to most points of the distribution. Although superficially similar to the notion of space-filling curves [26], the latter are fractal curves whereas our networks (having finite length) cannot have fractal curves.

A. Some rigorous results

Here we outline some rigorous results for this variant model, with details to be given in the companion paper [27].

Observe that given a straight line segment, the area within a small distance ε from the line is 2ε per unit length. So in a network of length L , the total area within that distance from the network is at most $2\varepsilon \times L$, and is reduced from that value by the presence of curved lines and intersections. By extending that argument one can prove [27] that the optimal network is always a tree (or a single curve, which is a special

case of a tree). For a nonisotropic density $\rho(\cdot)$ the optimal network may not be a single line, but we conjecture that for isotropic densities decreasing in r the optimal network is always a single curve.

Although $L \rightarrow \infty$ asymptotics are hardly realistic in the context of subway networks, the same questions might arise in some quite different context, so it seems worth recording the explicit result for asymptotics. In the $L \rightarrow \infty$ limit, the optimal network density (i.e., the edge length per unit area of the network) near point z should be of the form $L\phi[\rho(z)]$ for some increasing function ϕ . By scaling, the average distance from a typical point near z to the network should be $c_0/\{L\phi[\rho(z)]\}$ for some constant c_0 . So the overall average distance to the network is

$$\bar{d}(L) = \frac{c_0}{L} \int \frac{1}{\phi[\rho(z)]} \rho(z) dz. \quad (1)$$

The total length constraint implies that

$$\int \phi[\rho(z)] dz = 1. \quad (2)$$

A standard Lagrange multiplier argument shows that the integral in Eq. (1) is minimized, over functions ϕ under constraint Eq. (2), by a function of the form $\phi(\rho) = a\rho^{1/2}$, and then Eqs. (2) and (1) combine to show

$$\bar{d}(L)_{\text{opt}} = \frac{c_0}{L} \left[\int \rho^{1/2}(z) dz \right]^2. \quad (3)$$

Finally, the constant c_0 can be reinterpreted as the minimum average-distance-to-network in the context of networks on the infinite plane with network density = 1. From our initial “area within a small distance ε ” observation, the optimal network in the infinite context consists simply of parallel lines spaced one unit apart, for which $c_0 = 1/4$. So this analytic argument shows

$$\bar{d}(L)_{\text{opt}} \sim \frac{1}{4L} \left[\int \rho^{1/2}(z) dz \right]^2 \text{ as } L \rightarrow \infty. \quad (4)$$

This result makes no assumption about the underlying density ρ . In the Gaussian case, the integral in Eq. (4) equals $\sqrt{8\pi}\sigma$ and so $\bar{d}(L)_{\text{opt}} \sim \frac{2\pi\sigma^2}{L}$.

As explained in Ref. [27], what this argument actually shows is that a sequence of networks is asymptotically optimal as $L \rightarrow \infty$ if and only if the rescaled local pattern around a typical position z consists of asymptotically parallel lines with spacing proportional to $1/\phi \sim \rho^{-1/2}(z)$, but the orientations can depend arbitrarily on z . Visualize a fingerprint. For an isotropic density we can arrange such a network to be a spiral. This enables us to check the Gaussian prediction numerically. Consider a spiral of length L starting at some point $(a_L, 0)$ and with rings at radius r separated by $b_L \exp(r^2/4)$, and then optimize over (a_L, b_L) . Numerically we find slow convergence toward this limit behavior, shown in Fig. 4.

B. Numerical study: Different shapes

Unfortunately the asymptotics above say nothing about the actual shapes of the optimal networks for more realistic smaller values of L . Intuitively, we expect that for very small L the optimal network is just a line segment centered on the

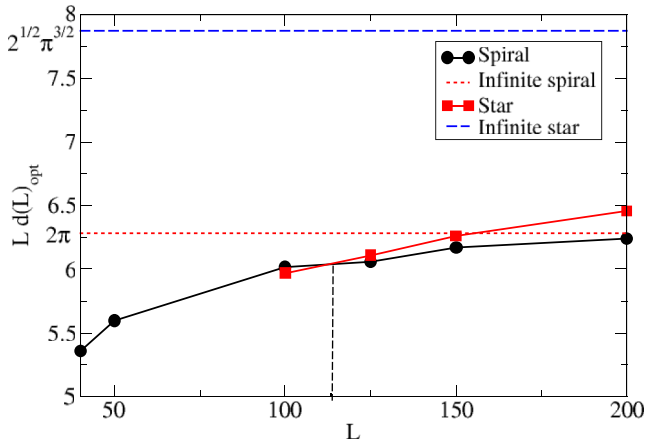


FIG. 4. Rescaled average distance $L\bar{d}(L)_{\text{opt}}$ versus L for the spiral and the star network (for the Gaussian disorder with $\sigma = 1$). For the spiral, we observe a slow convergence toward the theoretical limit 2π for gaussian disorder (horizontal dotted line). The convergence is even slower for the star network which converges to $2^{1/2}\pi^{3/2}$ (horizontal dashed line). For $L \approx 110$ (dashed vertical line) the spiral outperforms the star network.

origin. As L increases we expect a smooth transition from the line segment to a slightly-curved path, a “C-shaped” curve. But then how the optimal shapes transition to a tight spiral path (presumed optimal for very large L) is not *a priori* easy to guess.

We tested 8 shapes numerically for the standard Gaussian distribution, but we have to keep in mind that other shapes are in principle possible. For each shape the length is L , and we optimized over any free parameters (such as s in the 2×2 grid). The shapes considered here are the following ones:

- (1) The line segment $[-L/2, L/2]$.
- (2) The “cross” (two length $L/2$ lines crossing at the origin).
- (3) The “hashtag” or “ 2×2 grid” [Fig. 5(a)].
- (4) The “ring” (circle centered on the origin).
- (5) The “C-shape” [off-centered partial circle, with arc length 2θ removed, see Fig. 5(b)].
- (6) The “S-shape”: two arcs of circle of radius R and of angle 2θ , connected by a straight line of length $2R$ [see Fig. 5(c)].
- (7) The “star” with n_b branches of length r^* [so $r^*n_b = L$, see Fig. 5(d)].
- (8) The (Archimedean) “spiral”, $r = a\theta + b$.

Recall that the optimal (over all shapes) shape is always a path or tree, so the 2×2 grid or ring can never be overall optimal. Note also that (for any isotropic distribution) the optimal ring has radius equal to the median of the radial component of the underlying distribution, in our Gaussian case $\sqrt{2 \log 2} \approx 1.18$.

We simulated these different shapes in the Gaussian disorder case, and for each value of L we optimize over the parameters defining the different shapes. We note that for most shapes the variation interval of their parameters is small enough and we can scan it completely. There is therefore no problem of convergence, and the precision of the solution

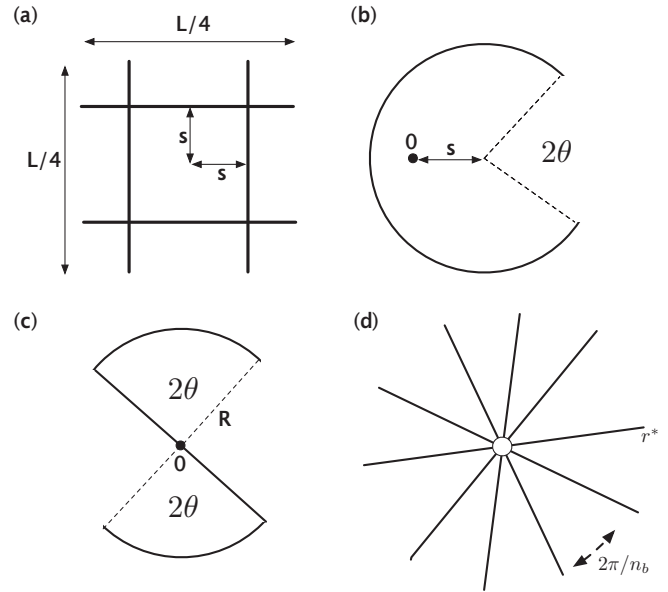


FIG. 5. Main shapes studied here (in addition to the line and the spiral). (a) The “hashtag” of 2×2 grid with parameter s . (b) The “C-shape” with parameters s and θ . (c) The “S-shape” with parameter θ . (d) The star network with n_b branches of size r^* .

found depends only on the number of points used to scan this interval. We show the results for these various shapes in Fig. 6.

The following general picture emerges (see also the Table I):

- (1) For small $L \lesssim 3.2$ the optimal shape is the C-shape. We note that for this shape the optimal θ decreases with L : for $L \approx 6$ we have $s = 0$ and for $L \approx 8.0$ the optimal $\theta = 0$. When $\theta = 0$ and $s = 0$ we then recover the ring result (see Fig. 7).
- (2) For $3.2 \lesssim L \lesssim 5.8$, the cross (star network with four branches) is optimal.
- (3) For $5.8 \lesssim L \lesssim 8.7$, the S-shape is optimal. We note that for this shape, as L increases, the optimal angle θ increases from 0 to $\pi/2$, but with a jump at $L \approx 5$ (see Fig. 8).

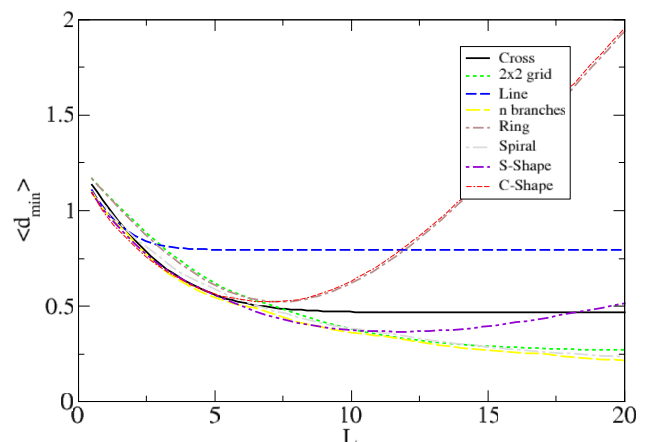


FIG. 6. Average distance to the network versus L for various shapes.

TABLE I. Numerical results for different total length L for the optimal shapes in the case of the optimal placement problem discussed in the main text.

Total length L	<3.2	$[3.2,5.8]$	$[5.8,8.7]$	$\gtrsim 8.7$
Optimal shape	C-Shape	Cross	S-Shape	Star network

(4) For $L \gtrsim 8.7$ the star network with n_b branches is the optimal shape. The number of branches is roughly increasing with L : $n_b \sim pL + q$ with $p \approx 0.4$.

(5) The simple Archimedean spiral was slightly less efficient than the star network over the range of L considered above: For $L = 20$, the average time is $\bar{d}_{\text{opt}} \approx 0.215$ for the star network, while for the spiral we have $\bar{d}_{\text{opt}} \approx 0.233$.

Qualitative discussion

In the examples above, the shapes were not adapted specifically to the Gaussian model (although the numerical parameters were optimized) and so are shapes one might consider for other isotropic distributions. Recall that our previous analysis of the $L \rightarrow \infty$ behavior found optimal networks to be spiral-like in a specific distribution-dependent way (near a point z , the rings are separated by distance proportional to $[\rho(z)]^{-1/2}$). For comparison, it is straightforward to show that the asymptotic behavior of the optimal star shape is $\bar{d}(L)_{\text{opt}} \sim 2^{1/2}\pi^{3/2}/L$, and numerical results are shown in the Fig. 4. By comparing with the spiral, we estimate that the value at which such spiral networks out-perform star networks in the Gaussian model is around $L = 110$.

Our numerics thus suggest there are 4 sharp transitions of shape: C-shape to cross near $L = 3.2$, cross to S-shape near $L = 5.8$, S-shape to star near $L = 8.7$ and finally a transition from the star network to the spiral near $L = 110$. But the star only slightly out-performs these curves, so it is possible that in fact there is a smooth evolution of curves as optimal networks. An alternative numerical approach is to seek the overall optimal network, via simulated annealing for example. This is computationally difficult, but some preliminary results for optimal curves are shown in Fig. 9 and are roughly consistent with our qualitative summary.

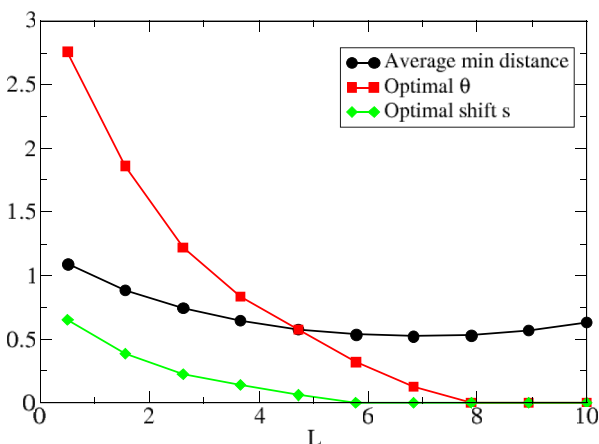


FIG. 7. Study of the C-shape with parameter s and θ .

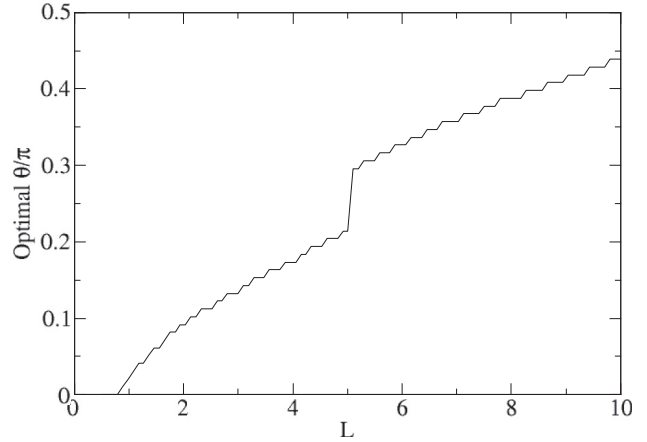


FIG. 8. Study of the S-shape: evolution of the optimal angle θ versus L .

IV. THE MINIMUM DISTANCE TO THE CENTER

For our second variant, closer to the general problem, we seek the network of length L that minimizes the average time to reach a designated “center” location. This was, for example, discussed in Refs. [21,22] where the case of street networks was considered and where the optimal tree was found. This problem in the context of a single line bus was also considered in Ref. [24] (and references therein). With respect to transportation systems such as subways or trains, this is obviously a crude simplification as we are in general interested in reaching many other stations and not a single location. As we will see in the rest of the paper, our results suggest that this simplified problem perhaps captures the essence of the general problem and might constitute a useful toy model where analytical calculations are feasible. As in our other variants we envisage each position on the network as a “station” where the subway is accessible.

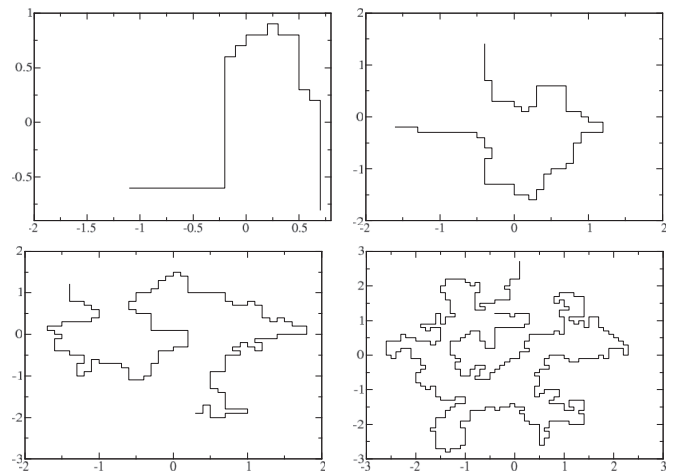


FIG. 9. Best configurations obtained with simulated annealing for different values of $L = 5, 10, 20, 50$. The simulations are obtained with a lattice polymer and using the pivot algorithm [28].

Taking as before an isotropic density $\rho(\cdot)$ and the origin as “center,” we seek the optimal network that minimizes

$$\bar{\tau} = \int \tau(z, 0) \rho(z) dz, \quad (5)$$

where $\tau(z, 0)$ is the minimum time to go from the point z to the origin 0 . The optimal network will depend on the ratio $S = v_s/v_w > 1$, where we recall that v_s is the speed within the network, and v_w the speed outside.

To simplify analytical calculations we assume in this variant that the paths from the points to the network can be made only along circular ($r = \text{const.}$) or radial ($\theta = \text{const.}$) lines. It remains true that the overall optimal network must be a path or tree. Indeed, if there is a cycle in the network, there is at least one point such that starting in either direction takes the same time to get to the center. One can then remove a small interval from that point and reattach elsewhere to get a better network.

However, we will consider only simple shapes for the network, starting from the star network and then adding a ring to it. As we will see below, for these structures we can develop simple analytical calculations and observe important phenomena such as a topological transition.

A. Star network

We first consider the star network, having n_b branches of lengths r^* , outward from the origin, evenly spaced with angle $2\pi/n_b$ spacing [see Fig. 5(d)]. So $L = n_b r^*$ and (for given L) n_b is a free parameter to be optimized over. By isotropy we can write

$$\rho(x, y) = \rho(r) \text{ for } r^2 = x^2 + y^2.$$

Again by isotropy, the average time $\bar{\tau}$ to the center is such that

$$\begin{aligned} \frac{1}{2n_b} \bar{\tau} = \int_0^{\pi/n_b} d\theta \left[\int_0^{r^*} dr r \rho(r) \left(\frac{\theta r}{v_w} + \frac{r}{v_s} \right) \right. \\ \left. + \int_{r^*}^R dr r \rho(r) \left(\frac{r - r^*}{v_w} + \frac{\theta r^*}{v_w} + \frac{r^*}{v_s} \right) \right]. \quad (6) \end{aligned}$$

In the following we will consider the uniform density on a disk and an exponentially decreasing density.

1. Uniform density

Here we take the uniform density $\rho(r) = \rho_0 = 1/(\pi R^2)$ on a disk of radius R . Without the network the average time to reach the center is $\tau_0 = 2R/(3v_w)$. Write $\eta = 1/S = v_w/v_s$, and assume that taking the subway is always better than walking directly to the center, which is the condition that $\eta \leq 1 - \pi/n_b$. Write $u^* = r^*/R$ (the branch length relative to city radius) and $u_0 = L/R$ (network length relative to city radius) and $\chi = \pi/n_b$. Evaluating the integrals in Eq. (6), the average time $\bar{\tau}$ to reach the center via subway satisfies

$$\frac{\bar{\tau}}{\tau_0} = \frac{u^{*3}}{2} \left[-\frac{\chi}{2} - \eta + 1 \right] - \frac{3}{2} u^* \left[-\frac{\chi}{2} - \eta + 1 \right] + 1. \quad (7)$$

For given L we want to optimize over the free parameter r^* , that is over u^* . From $L = n_b r^*$ we obtain $\chi = \pi u^*/u_0$ and

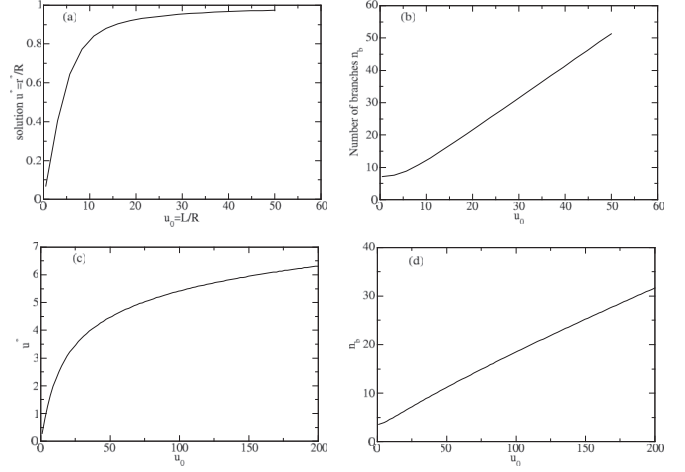


FIG. 10. We show here the result of the minimization of the average time for the star network with parameters n_b and r^* with the constraint $L = n_b r^*$. On the left (a, c) we show the length of branches r^* versus $u_0 = L/R$ and on the right (b, d) the number of branches n_b versus u_0 (here $\eta = 1/8$). The top row corresponds to the uniform density case and the bottom one to the exponential density.

then the average time as a function of u^* reads

$$\frac{\bar{\tau}}{\tau_0} = \frac{1}{2} (u^{*3} - 3u^*) \left[-\eta + 1 - \pi \frac{u^*}{u_0} \right] + 1. \quad (8)$$

Minimizing this quantity over u^* leads to a polynomial of degree 3, and the behavior of the solution is shown numerically in Fig. 10. As is intuitively obvious, for large $u_0 = L/R$ it is optimal to use roughly u_0 branches of length almost R ; more precisely for $u_0 \gg 1$ we obtain

$$\begin{aligned} u^* = 1 - \frac{\pi}{3(1-\eta)u_0} + \mathcal{O}\left(\frac{1}{u_0^2}\right) \\ n_b = u_0 + \mathcal{O}(1). \quad (9) \end{aligned}$$

Perhaps less obvious is the initial behavior over $0 \leq u_0 \leq 10$, where the length of branches is increasing faster than their number. In other words we first observe a radial growth and then an increase of the number of branches.

2. Exponential density

In this case, we take the density of the radial component to be $\rho_0 r \exp(-r/r_0)$ on the infinite plane. Without the network the average time to reach the center is $\tau_0 = 2r_0/v_w$. Evaluating the integrals in Eq. (6), the average time $\bar{\tau}$ to reach the center via subway satisfies

$$\frac{\bar{\tau}}{\tau_0} = \frac{\pi u^*}{2u_0} + \eta - e^{-u^*} \left(\frac{\pi u^*}{u_0} + \eta - 1 \right) \left(\frac{u^*}{2} + 1 \right), \quad (10)$$

where $u^* = r^*/r_0$ and $u_0 = L/r_0$. We can plot this function and look numerically for the minimum. The results are shown in Fig. 10 (bottom).

We observe here that for large resources ($u_0 \gg 1$) the number of branches scales as $n_b \sim a u_0$ with $a \approx 0.1$ and the solution u^* seems to converge slowly to some value that depends on η . Here also, the number of branches increases only after the radial growth.

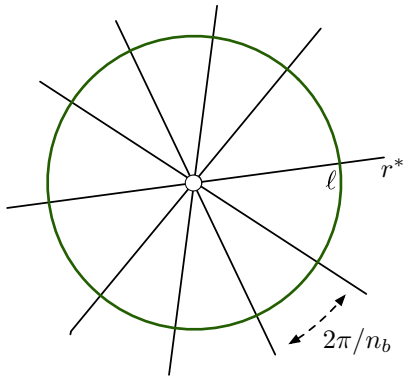


FIG. 11. Schematic of the star network combined with a ring. We have now three parameters: the number of branches n_b , the length r^* of the branches, and the radius ℓ of the ring.

B. Loop and branches

We now consider a more interesting case where we have n_b branches of length r^* and a ring of radius ℓ (see Fig. 11). This

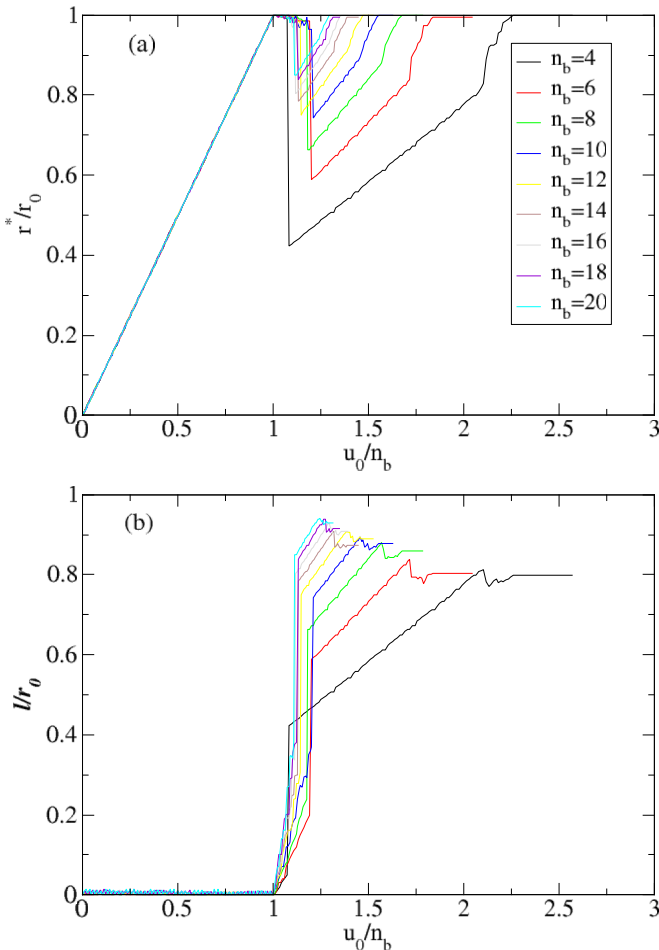


FIG. 12. Uniform density: results for the star+loop network for different values of n_b . (a) Normalized radius of the ring. (b) Normalized length of branches. We normalized u_0 by n_b to get the same “transition” point at $u_0/n_b = 1$. These results are obtained for $\eta = 1/8$.

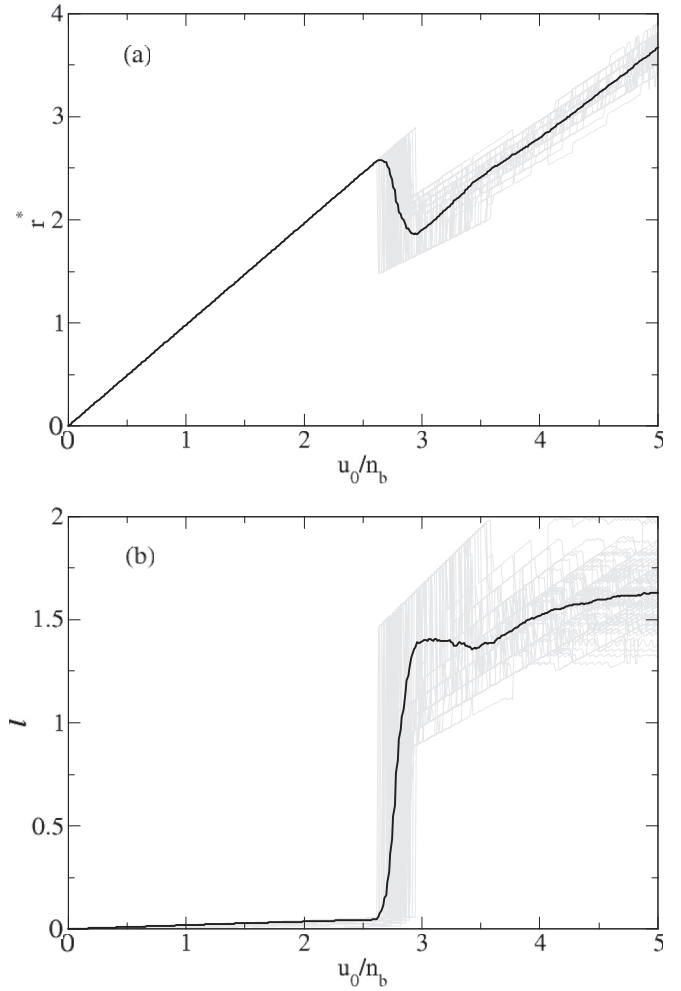


FIG. 13. Gaussian density ($\sigma = 1$): results for the star+loop network for $n_b = 8$. (a) Size r^* of the branches. (b) Radius of the ring. These results are averaged over 100 configurations and are obtained for $\eta = 1/8$. The gray curves represent the results for each configuration.

case is essentially motivated by subway networks that seem to display this type of structure when they are large enough [2]. We have three parameters: n_b , ℓ , and r^* , where $\ell \leq r^*$ for connectivity. The total length of the network is

$$L = 2\pi\ell + n_b r^*. \tag{11}$$

This network enables us to study the relative contributions of loop and branches to our goal of minimizing the average time to go to the center. This case is analytically difficult, so we study it numerically with a simulation.

We first consider the uniform distribution on a disk of radius r_0 and again choose $\eta = 1/8$ (which corresponds to the reasonable values $v_w \approx 5$ km/h and $v_s \approx 40$ km/h). We first study the case where n_b is fixed and where we optimize the network over r^* and ℓ . In Fig. 12, we show the results for the optimal value of r^* and ℓ versus $u_0 = L/r_0$ normalized by n_b . We observe that when resources are growing from 0, we have only a radial network ($\ell = 0$). At $u_0/n_b = 1$ we have a “transition” point where a loop appears. This means that until $u_0 = n_b$ all the available resource is converted into the

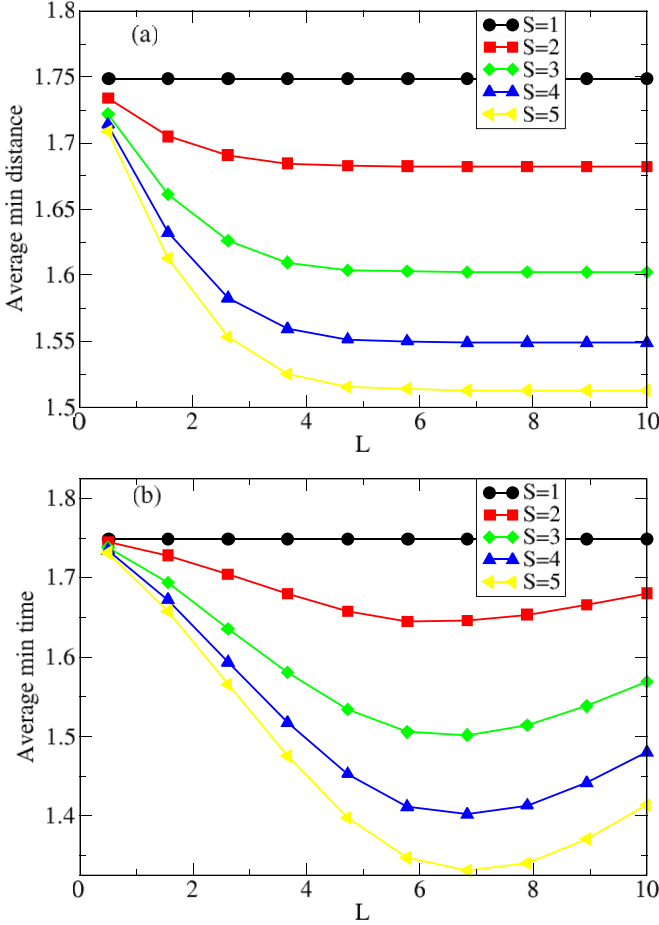


FIG. 14. Average journey time in the Gaussian case for different values of S and for (a) a line $[-L/2, L/2]$ and (b) a ring of radius $R = L/2\pi$.

radial structure. When the radial structure is at its maximum ($r^* = r_0$) we observe the appearance of a loop whose diameter is then increasing with u_0 .

We note that even if both the number of branches and the size of the loop undergo a discontinuous transition, the average minimum time displays a smooth behavior. Also, if we increase further the total length L , it will result in a larger number of branches n_b .

In the uniform density case, the domain is finite (a disk of radius R) and at fixed value of n_b , there is therefore a maximum value of $L_{\max} = n_b R + 2\pi R$. For larger values of L , the optimal network will increase its number of branches n_b . It is different in the Gaussian disorder case: the domain is infinite and there is no obstacle to have a fixed value of n_b with size r^* growing indefinitely with L . We can thus expect some differences with the uniform density case. We repeated the calculations above for 100 configurations and the average together with the results for each configuration are shown in Fig. 13 (here $u_0 = L/\sigma$). We still observe the different regimes separated by an abrupt transition: the first regime where the size of branches grows with L and the second regime where there is a ring whose size grows very slowly with L . In contrast with the uniform density case, the

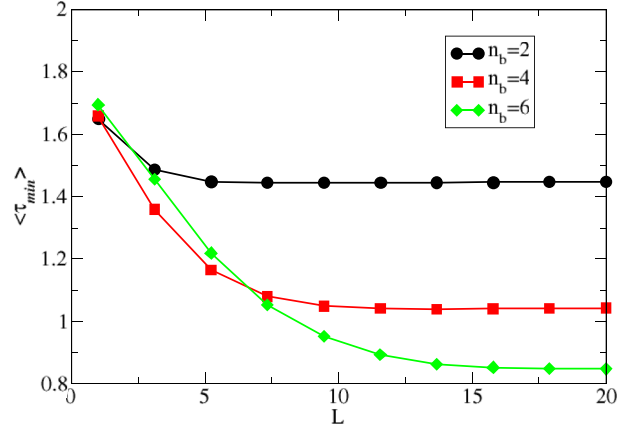


FIG. 15. Average journey time (in the Gaussian case) for star networks with different number of branches ($n_b = 2, 4, 6$).

transition takes place for a value u_0/n_b that fluctuates in the range $[2.5, 3.0]$.

V. THE GENERAL MODEL

As discussed in the Introduction, we will now consider the “general” setting of routes between arbitrary points z_1 and z_2 . The route can either go straight (speed v_w) from z_1 to z_2 without using the network, or go $z_1 \rightarrow A_1 \rightarrow A_2 \rightarrow z_2$, where A_1 and A_2 are “stations” (any points on the network) and where travel from A_1 to A_2 is within the network at speed v_s , and the other journey segments are straight at speed v_w . In a companion paper [27] we study the more realistic model where the route is optimized over choice of A_1 and A_2 , but here we take each A_i as the closest station to z_i . Unlike previous cases, the overall optimal network is not necessarily a tree.

A. Various shapes

We present results for various simple shapes, for the standard Gaussian density. We start with the line segment and the ring and the results for different values of S are shown on Fig. 14. For these two shapes, we observe the same behavior as in the time to center problem: For the line there is a quick saturation to a constant, and for the ring there is a minimum at $L \approx 2\pi\sigma$.

We also consider the case of the star network with n_b branches and the result is shown on Fig. 15. We observe (see also the Table II that for $0 < L \lesssim 1.15$ the line is optimal. For $1.15 \lesssim L \lesssim 6.6$, the cross $n_b = 4$ is the optimal choice, while for $L \gtrsim 6.6$, the solution $n_b = 6$ is better. Very likely we will have (as in the previous case of the average time to the center) an optimal network with $n_b \propto L$.

TABLE II. Numerical results for the optimal shapes for the general model for different total length L .

Total length L	< 1.15	$[1.15, 6.6]$	$\gtrsim 6.6$
Optimal shape	Line	Cross ($n_b = 4$)	Star ($n_b = 6$)

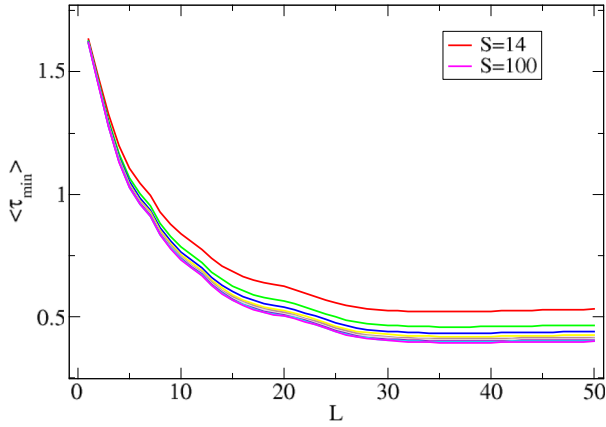


FIG. 16. Average time (Gaussian density) for n_b branches plus a loop for values of S from 14 to 100.

B. Loop and branches: Scaling of the average time

We focus here on the case where the network is made of n_b branches of length r^* and a loop of radius ℓ . So $L = n_b r^* + 2\pi \ell$. We take n_b and ℓ as the 2 free parameters over which we will minimize the average time. The optimized average time $\bar{\tau}_{\min}$ for different values of S is shown in Fig. 16. Naively one expects that this quantity behaves as

$$\bar{\tau}_{\min} = \frac{a}{\sqrt{L}} + \frac{b}{S}, \tag{12}$$

where the first term of the right-hand side corresponds to the average distance to the network and which we expect to scale as $1/\sqrt{L}$. The second term corresponds to the shortest path distance within the network. In principle, a and b could depend on L . If we assume this form to be correct then $S\bar{\tau}_{\min}$ versus $X = S/\sqrt{L}$ should be a straight line. We tested this assumption on the data from Fig. 16 and the result is shown in Fig. 17. This good collapse (except for deviations observed for large values of S/\sqrt{L}) supports the assumption Eq. (12).

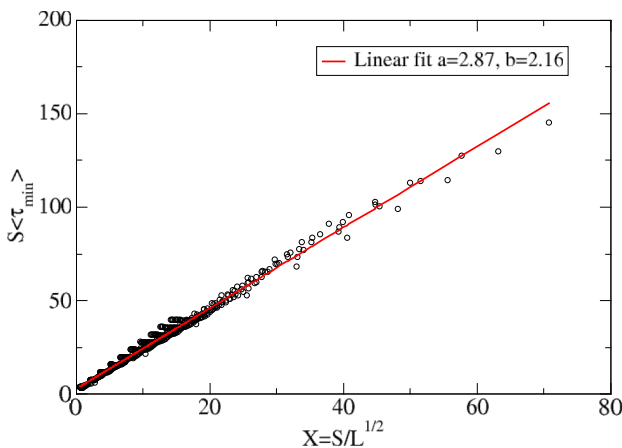


FIG. 17. Rescaled average time $S\bar{\tau}_{\min}$ versus the rescaled variable S/\sqrt{L} .

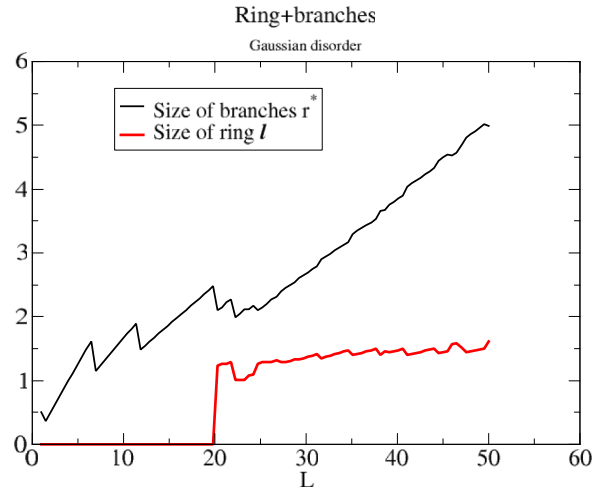


FIG. 18. Optimal length of branches and optimal size of the loop versus the total length L (for gaussian disorder): typical shape for r^* and ℓ . As in the case of the quickest path to the origin, we observe a sharp transition for $L \approx 20\sigma$ where a loop of radius $\ell \approx \sigma$ appears (here $\eta = 1/2$).

C. Loop and branches: A topological transition

Still in the branches and loop model, we observe (Fig. 18) a transition: r^* grows almost steadily with $\ell = 0$, until a transition value at $L_c \approx 20$ where the ring appears. Although the structure changes abruptly it is interesting to note that there is no discontinuity in the average minimum time. The size of the ring stays stable with $\ell \approx \sigma$ (the Gaussian standard deviation). Naively, we can say that the ring appears when the branches can have a length $r^* \approx 2\sigma$ and a loop of size $\ell \approx \sigma$ which gives the condition $L_c \approx n_b \sigma + 2\pi \sigma$. At the transition, we observe that we have $n_b \approx 8$ which then gives $L_c \approx 22$, not too far from the value $L_c = 20$ observed here.

The quantity L_c is independent from S which is expected, as it is essentially controlled by the topology of the network. We note that this transition was already observed in the previous case “minimum distance to the center.” As L increases the optimal number of branches grows roughly from 2 to 10. The picture that emerges here is consistent with the empirical study [2]: we observe a ring around the “core” of the city and then branches radiating from it. More generally, these results suggest that the distance to center problem is a reasonably good proxy for the more general problem.

VI. DISCUSSION

Algorithmic aspects of network design questions similar to ours have been studied within computational geometry (e.g., Ref. [24] chapter 9) and “location science” (e.g., Ref. [25]). But our specific question—optimal network topologies as a function of population distribution and network length—has apparently not been explicitly addressed. Although real-world networks are probably not optimal and result from the superimposition of many different factors, understanding theoretically optimal networks could give some information about the actual structure observed in many cases. For example, it

could help us to understand the seemingly universal structure displayed by very large subway networks [2].

Even for simple models, optimizing over all possible topologies is difficult, so we investigated only various simple shapes. We provided general arguments and analytical calculations in simple cases and most of our analysis is numerical. In general, we expect an evolution of the shape of optimal networks when L increases, with the possible existence of sharp transitions between different shapes. Although we were not able to prove this in general, we observed such transitions in simple cases such as branches and a loop: in the case

of Gaussian (variance σ^2) population density, starting from a small value of L the branches first grow smoothly, then suddenly for a value L_c we observe the appearance of a loop of size $\ell \sim \sigma$. This transition also exists in the case of uniform density.

It would be interesting to see these transitions of overall optimal networks obtained numerically, and this might be feasible in some cases with a simulated annealing type of algorithm. In any case these problems suggest theoretical questions and practical applications which certainly deserve further studies.

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