

Apollonian networks

José S. Andrade Jr. and Hans J. Herrmann*
*Departamento de Física, Universidade Federal do Ceará,
60451-970 Fortaleza, Ceará, Brazil.*

Roberto F. S. Andrade
*Departamento de Física, Universidade Federal da Bahia,
40210 Salvador, Bahia, Brazil.*

Luciano R. da Silva
*Departamento de Física, Universidade Federal do Rio Grande do Norte,
59072-970 Natal, Rio Grande do Norte, Brazil.*

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We introduce a new family of networks, the Apollonian networks, that are simultaneously scale-free, small world, Euclidean, space-filling and matching graphs. These networks have a wide range of applications ranging from the description of force chains in polydisperse granular packings and geometry of fully fragmented porous media, to hierarchical road systems and area-covering electrical supply networks. Some of the properties of these networks, namely, the connectivity exponent, the clustering coefficient, and the shortest path are calculated and found to be particularly rich. The percolation, the electrical conduction and the Ising models on such networks are also studied and found to be quite peculiar. Consequences for applications are also discussed.

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The study of networks has fruitfully inspired the understanding of transport and information flow within systems of many degrees of freedom during the last years [1–4]. Many network types have been proposed and investigated serving to differentiate and elucidate effects ranging from clan-formation, epidemics spreading and logistic planning to earthquake prediction, neural activity and immunological defenses [1–4].

Among a multitude of models, much attention has been dedicated recently to the study of scale-free networks, namely, networks that display a power-law degree distribution, $p(k) \propto k^{-\gamma}$, where k is connectivity (degree) [1]. The widespread appearance of networks with fat-tailed degree distribution in Nature has been mainly justified by the fact that their evolution is self-organized in a way that hub elements are naturally generated and represent the dominant constituents of the network [5].

There are, however, several conceptual and applied aspects of scale-free network models that are still under investigation. For instance, the fact that networks with exponent $\gamma > 2$ can be embedded in regular Euclidean lattices has motivated Rozenfeld *et al.* [6] to develop a method for generating random scale-free networks with well defined geographical properties. The *ultrasmall* characteristic found for the diameter of random scale-free networks [7] is also an intriguing aspect of these structures that is expected to explain anomalies in their diffusional and transport phenomena behavior. Finally, the

stability to crashes due to removal of sites in such networks has also been the focus of intense research activity [8]. These studies revealed that random scale-free networks remain connected even if nearly all of their nodes break down, as long as the degree exponent $\gamma \leq 3$. As a consequence of this striking property, the Internet and other well known networks displaying scale-free behavior must be resilient to random breakdown.

An important issue that has been much less explored in network science is the design problem of a suitable complex network for a given system where connectivity plays an essential role. For this purpose, *deterministic* networks represent the ideal strategy, since they are controllable and can therefore be subjected to the particular constraints of the problem, for example, those related to space, time, economical and other types of limitations. Using deterministic models, it should be possible to outline some specific guidelines for the design of real networks with desired properties (e.g., high clustering, compactness, etc.). Some examples of deterministic models that are scale-free have been recently proposed and successfully used to describe random growing networks [9, 10], but they have eluded the possibility of being embedded in Euclidean space. In this letter we introduce a class of networks, named Apollonian networks, that can be either deterministic or random, are scale-free, display small world effect, can be embedded in an Euclidean lattice, and show space-filling as well as matching graph properties.

To define our network in its simplest deterministic version let us start with the problem of space-filling packing of spheres according to the ancient Greek mathematician Apollonius of Perga [11]. In its classical solution, three

* Also at Institute for Computer Physics 1, University of Stuttgart
email: hans@ica1.uni-stuttgart.de

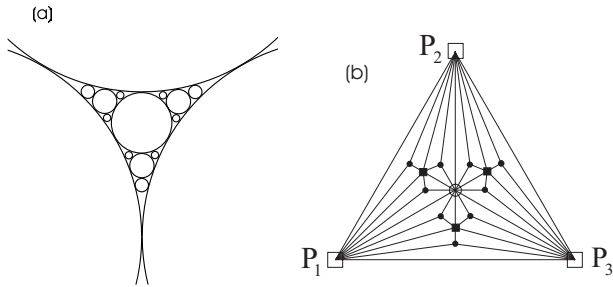


FIG. 1: (a) Classical Apollonian packing. (b) Apollonian network; first, second and third generation are symbols \circ , \blacksquare and \bullet respectively.

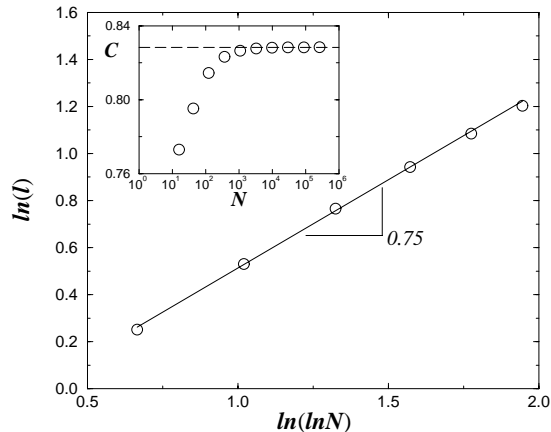


FIG. 2: Shortest path l as a function of the number of sites N . The solid line is a guide to the eye with slope $3/4$. The inset shows the semi-log plot of the clustering coefficient C as a function of N . The dashed line is a guide to the eye for $C = 0.828$, observed at large values of N .

circles touch each other and the hole between them is filled by the circle that touches all three, forming again three but much smaller holes that are then filled again each in the same way as shown in Fig. 1(a). The circle size distribution follows a power-law with exponent of about 1.3 [11]. In fact there exist many other topologies with different fractal dimensions [12]. This procedure can also be generalized to higher dimensions [13].

Apollonian tilings can describe dense granular packings and have also been used as toy models for turbulence and fragmentation. Connecting the centers of touching spheres by lines one obtains a network which in the classical case of Fig. 1(a) gives a triangulation that physically corresponds to the force network of the packing. We will call the resulting network shown in Fig. 1(b) an “Apollonian network”. Besides resembling the graphs introduced by Dodds [14] for the case of random packings, this network has also been used in the context of porous media [15].

First we show that Apollonian networks are scale-free.

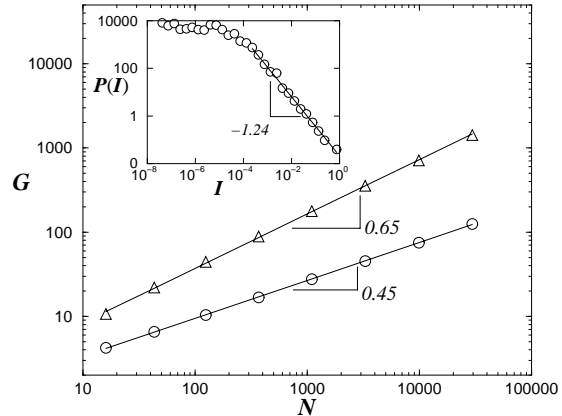


FIG. 3: Conductance G as function of the number N of sites when a potential is applied either between the center and all the sites of the last generation (upper curve) or between two corners of the network (lower curve). The inset shows the distribution of local currents for the first case.

From Fig. 1(b) one can see that at each generation n the number of sites N increases by a factor three and the coordination of each site by a factor two. More precisely, at generation n ($n = 0, 1, 2, \dots$) there are $m(k, n) = 3^n, 3^{n-1}, 3^{n-2}, \dots, 3^2, 3, 1$, and 3 vertices with degree $k = 3, 3 \times 2, 3 \times 2^2, \dots, 3 \times 2^{n-1}, 3 \times 2^n$, and 2^{n+1} , respectively, where the last number of vertices and degree correspond to the three corners, P_1, P_2 , and P_3 . Due to the discreteness of this degree spectrum, it is convenient to work with the cumulative distribution $P(k) = \sum_{k' \geq k} m(k', n)/N_n$, where $N_n = 3 + (3^{n+1} - 1)/2$ is the number of sites at generation n . In order to compute the analog to our problem of the degree exponent γ , as commonly defined for continuum distributions [10], it is easy to show that $P(k) \propto k^{1-\gamma}$, with $\gamma = 1 + \ln 3 / \ln 2 \approx 2.585$.

Next, we show that Apollonian networks display *small-world effect* [3, 5, 16]. Accordingly, this means that the average length of the shortest path l between two vertices as defined in ref. [17] should grow slower than any positive power of the system size N . For the network in Fig. 1(b) we find that $l \propto (\ln N)^\beta$, with $\beta \approx 3/4$ as can be seen in Fig. 2. This is a novel intermediate behavior between *small* ($l \propto \ln N$) and *ultrasmall* ($l \propto \ln \ln N$) networks [6].

The second property characterizing a small world network is the clustering coefficient C as defined in ref. [17]. We find it to be 0.828 in the limit of large N , as shown in the inset of Fig. 2. This is a large value, comparable for instance with the cluster coefficient for the collaboration network of movie actors $C = 0.79$ [17]. Consequently, since L grows logarithmically and C is close to unity, the Apollonian network indeed describes a small world scenario [17].

As opposed to hierarchical lattices [10] used for instance in the Migdal-Kadanoff approximation, Apollonian networks are embedded in Euclidean space and can

therefore describe geographical situations. In the case of Fig. 1(a) the sites form a multifractal point set in the asymptotic limit of infinitely many iterations [18]. In the Apollonian networks for $n \rightarrow \infty$, the bonds do not only completely cover the space (like a Peano curve), but also never cross each other. In this situation we have what is called a “matching graph” which is not the case for any other known scale-free network [1].

Now let us explore the properties of some well-known simple models defined on the lattice shown in Fig. 1(b). Thinking of an electrical supply system where the central site is the source (power station), the last generation sites are sinks (consumers), and all the connections have the same conductance, one can calculate the equivalent conductance G of the network. Going from one generation to the next, the number of parallel system outputs increases by a factor three while at each node the number of outputs doubles. Due to the self-similarity, one has therefore doubled the conductance while increasing the number of sites by three. As a result, G follows a power-law, $G \propto N^z$, with $z = 2/3$. As shown in Fig. 3, this exponent can be confirmed through computational simulation of the resistor network model. From Kirchhoff’s law, the resulting system of linear algebraic equations are numerically solved using a sparse matrix inversion technique. This solution also allows us to compute the distribution of local currents $P(I)$, as shown in the inset of Fig. 3. Interestingly it follows a power-law for large values of I with an exponent -1.24 , as a consequence of the hierarchical choice of the output sites.

One can alternatively apply a potential drop between two corners of the system, i.e. P_1 and P_2 in Fig. 1(b). The resulting conductance numerically calculated as a function of the size of the network gives a power-law too, but with exponent 0.45 as shown in Fig. 3.

We now proceed with the study of bond percolation simultaneously applied among the three points P_1, P_2 and P_3 of Fig. 1(b) removing, however, the three direct connections between these points. Similarly to ref. [8], we find that the percolation threshold p_c goes to zero as the number of sites increases, according to a power-law, as seen in Fig. 4. Assuming $p_c \propto \sqrt{N}^{-\frac{1}{\nu}}$, the slope yields an exponent $\nu \approx 3$.

Spin models can be defined on the Apollonian lattice in a variety of ways. We consider here that an Ising spin s_i is placed on each site of the lattice. Between two sites we have a pair interaction constant J_n , where n indicates that the link between the interacting spins is placed at the n -th generation of the construction of the lattice. Moreover, the interactions are considered to be ferromagnetic $J_n > 0$, decaying with n as $J_n \propto n^{-\alpha}$, and insensitive to the actual distance between the spins. With this model definition, it is straightforward to use a transfer matrix formalism to write down temperature dependent recurrence relations for the free energy f_n and correlation length ξ_n of the model at two subsequent generations, $f_{n+1} = f_{n+1}(f_n, \xi_n; T)$ and $\xi_{n+1} = \xi_{n+1}(f_n, \xi_n; T)$ [19, 20]. Exact values for these and any other functions

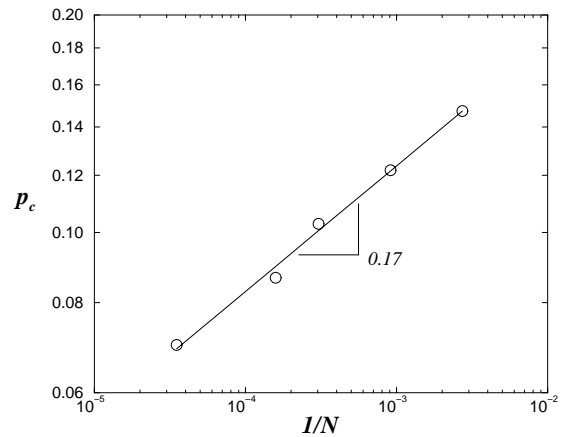


FIG. 4: Double logarithmic plot of the percolation threshold p_c as function of the inverse system size N .

in the thermodynamical limit $n \rightarrow \infty$ can be obtained through the numerical iteration of f_{n+1} and ξ_{n+1} and for their derivatives. The iteration process n is stopped when the free energy per spin is the same in two subsequent generations within the first 16 digits.

The results obtained here are quite different from those for other self-similar lattices. The free energy, entropy, specific heat and magnetization (respectively f, s, c, m) are found to be completely smooth for all values of T . A classical Schottky maximum dominates the behavior of c while s increases monotonically to $k_B \ln 2$. The presence of long-range order is observed as $m = 1$ at low values of T . On the other hand, when T is large, $m \rightarrow 0$ as $\exp(-T)$ for $\alpha = 0$, with no noticeable presence of a critical temperature. For $\alpha > 0$, we find a stronger decay, as $m \sim \exp(-T^\lambda)$. The results for the correlation length are more subtle. ξ diverges at low temperatures, expressing the evidence of long-range order. As T increases beyond a given $T_c(n)$ it converges to a well defined value. However, if the iteration procedure is pursued to a value of n larger than the one required for the convergence of f_n , we observe that ξ keeps on diverging within a larger T interval. This behavior therefore suggests the existence of an n dependent effective critical temperature $T_c(n)$, as has been found by other authors for spin models on another scale-free lattice [21]. In Fig. 5 we show how $T_c(n)$ depends on n for different values of α . The power-law $T_c(n) \sim n^{\tau(\alpha)}$, with τ going continuously from $\tau(0) = 1$ to $\tau(\infty) = 1/2$ indicates a novel kind of critical behavior.

It is important to mention that a more general version of the network shown in Fig. 1(b) is to choose at generation n in each triangle a new site randomly and connect it to the three adjacent sites. In this sense the network can describe the porous fine structure inside a block of heterogeneous soil surrounded by larger pores or as the network of roads or supply lines going to smaller urban units surrounded by larger ones. There exists in fact a very large class of Apollonian networks obtained not only

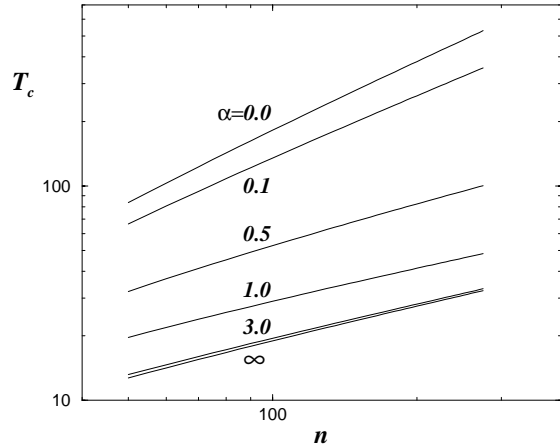


FIG. 5: Double logarithmic plot of the critical temperature as function of the generation number n for different exponents α .

by changing the choice of the position of the sites inside the areas or changing the initial graph, but also having a different topology as classified in ref. [22]. All these networks have the properties presented here, however, with different exponents if the topology is different.

Apollonian networks have the typical properties of the complex graphs in nature and society: large clustering coefficients, slower than logarithmic increase of the shortest path with number of sites, and a power-law degree distribution. In the context of critical phenomena, we did not find a finite critical point neither for percolation nor for the Ising model on Apollonian networks. The exponent $\nu = 3$ controlling how the percolation threshold goes to zero with N is unusually high while $T_c(n)$ of the Ising model diverges with a power-law in the number n of gen-

erations.

Considering the description of the force network in a polydisperse packing, the small world nature of the lattice implies that between any two grains there are only a few contacts at best. If the medium is pre-constrained, the electric conductance and elastic response have the same divergence [23], and we find that the system becomes more rigid with the inclusion of smaller particles following a power-law (with exponent 0.45 in our topology) in the number of particles. Giving to each grain a remnant magnetisation as discussed in ref. [24], our result for the Ising model implies that, in the limit of many particles, one always find a ferromagnetic response.

Interpreting our network as a porous medium, the fact that $p_c = 0$ is compatible with Archie's law, namely, that there exists no finite critical porosity and the medium always percolates. If the network represents roads or electric supply lines between cities implies that they have small world character and that the distribution of car flux or electrical currents follows a power-law when going from larger to smaller sites. The results for the Ising model imply that opinions or cooperations can stabilize at any degree of interaction, and the percolation threshold being zero means that in the thermodynamic limit the global connectivity cannot be disrupted, no matter how many connections are broken.

We have seen that the Apollonian networks introduced in this paper can have several applications yielding reasonable conclusions while on the other hand their critical properties are rather special. They should be studied in more detail including synchronization, spreading, path-optimization, search algorithms and more specific features of the real systems.

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