Interactively Uncluttering Node Overlaps for Network Visualization

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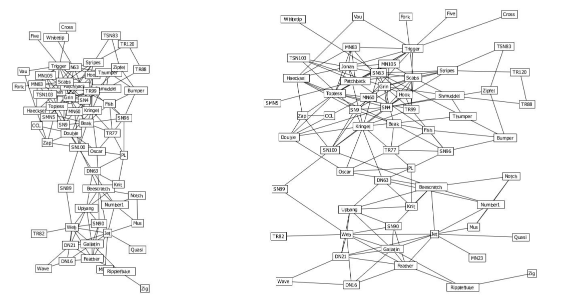
***Abstract*—Visual interaction with networks have been promising in the sense that we can successfully elucidate underlying relationships hidden behind complicated mutual relationships such as co-authorship networks, product co-purchasing networks, and scale-free social networks. However, it is still burdensome to alleviate visual clutter arising from overlaps among node labels especially in such interactive environments as the networks become dense in terms of the topological connectivity. This paper presents a novel approach for dynamically rearranging the network layouts by incorporating centroidal Voronoi tessellation for better readability of node labels. Our idea is to smoothly transform the network layouts obtained through the conventional force-directed algorithm to that produced by the centroidal Voronoi tessellation to seek a plausible compromise between them. We also incorporated the Chebyshev distance metric into the centroidal Voronoi tessellation while adaptively adjusting the aspect ratios of the Voronoi cells so that we can place rectangular labels compactly over the network nodes. Finally, we applied the proposed approach to relatively large networks to demonstrate the feasibility of our formulation especially in interactive environments.**

***Keywords*-Centroidal Voronoi tessellation; node labels; Chebyshev distance; interactive environments;**

I. Introduction

Annotated node networks provide an effective means of visualizing various kinds abstract relationships such as co-authorship networks, product co-purchasing networks, friendship networks, etc. This often becomes possible by taking advantage of conventional graph drawing techniques, while it is hard to retain the high readability of such networks especially when the networks are dense in terms of topological connectivity since, in that case, text labels associated with nodes are more likely to overlap with each other. Figure 1(a) shows a layout of a dolphin social network [1] obtained by the conventional force-directed algorithm where text labels overlap with each other especially when the corresponding nodes have high degree in the network.

This paper presents a novel approach for sparing enough space around the annotated nodes to avoid such label overlaps, by integrating Voronoi tessellation into the conventional force-directed algorithm. In our approach, the network visualization starts from the layout obtained through the conventional force-directed algorithm and then gradually transforms it into a Voronoi-based layout to seek a plausible compromise between the two layouts. The centroidal Voronoi tessellation is employed to accelerate the process for sparing enough space around the annotated nodes especially for the interactive environments. Several enhancements based on anisotropic Chebyshev distance are also incorporated to place rectangular node annotation labels compactly within the screen space. Figure 1(b) presents an improved layout of the dolphin social network where the territory of each node label is sufficiently reserved to avoid mutual overlaps. Our approach also facilitates us to interactively turn on/off the annotations of individual nodes even when the network layout is still under transformation, and thus provides an effective means of visualizing a large-scale network by interactively annotating subsets of its nodes.



(a) (b)

Figure 1. Undirected social network of frequent associations between 62 dolphins in a community living off Doubtful Sound, New Zealand [1]: (a) layout with the conventional force-directed approach. (b) our approach.

The remainder of this paper is organized as follows: Section II provides a brief survey on previous approaches relevant to ours. Section III describes details of our proposed approach for sparing the space around the annotated nodes in the network layout. Section IV introduces several enhancements incorporated into our approach so that we can maximize the screen space usage when laying out the annotated network. Section V exhibits several experimental results together with the comparison with previous approaches, which is followed by the conclusion of this paper together with possible future extensions in Section VI.

II. Related Work

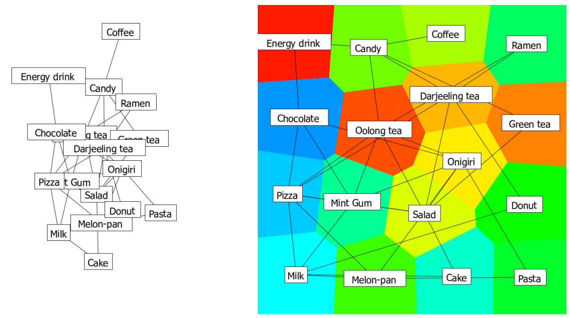
Network visualization is an important theme for information visualization and several techniques have been developed for visually analyzing complicated networks such as social networks [2]. In this technique, improving the visual readability is one of the challenging problems and for that purpose a large number of graph layout techniques were invented. The force-directed algorithm formulated by Eades [3] is the most popular approach for laying out such networks. This approach models the nodes and links of the network as electrical charges and springs, and allows us to find a visually pleasing layout of the network as an equilibrium state where drawing forces by the springs and repulsive forces between electrical charges are balanced. For calculating the spring forces, Hooke's law is often employed [4]. The force-directed algorithm basically facilitates us to improve the readability of the network layout since it empirically eliminates unwanted visual clutter such as edge crossings and node overlaps. Furthermore, Gansner et al. [5] successfully allocated enough space around each node for its annotation, while retaining their initial layout obtained by the conventional force-directed approach. Dwyer et al. [6] rearranged the node labels to maximize the space coverage of the screen space while retaining their orderings along the horizontal and vertical axes.

On the other hand, space partitioning techniques including Voronoi tessellation effectively subdivided the screen space into a specific number of cells, each of which is associated with a seed point. Thus the Voronoi tessellation is often employed to seek the plausible layout of the network for allocating equivalent space to each of its nodes. Several techniques have been proposed for laying out networks by clustering nodes based on Voronoi-based recursive subdivisions [7], and for avoiding overlaps among nodes by taking advantage of the Voronoi tessellation [8][9]. In addition, Wu et al. [10] employed the Voronoi diagrams for allocating space for annotation labels in railway maps, and Brivio et al. [11] introduced the centroidal Voronoi as a basement for browsing images compactly within the screen space.

Internal and external labeling techniques are also relevant, where internal labeling places annotation labels in the vicinity of the network nodes while external labeling seeks space for annotation labels around the boundary of the drawing area. Several techniques have been proposed for annotating schematic networks such as railway and metro maps [12][13][14]. The conventional force-directed approach has also been applied to map annotation where the mutual overlaps between labels are successfully eliminated by applying repulsive forces based on the coulomb model [15].

III. Approach for Drawing Annotated Networks

As described earlier, our approach can be considered as a hybrid one in the sense that it explores a reasonable compromise between the network layouts obtained by the force-directed algorithm and centroidal Voronoi tessellation. In practice, our hybrid approach first initializes the network



(a) (b)

Figure 2. Layouts of an artificial product co-purchasing network obtained by (a) the conventional force-directed algorithm and (b) centroidal Voronoi tessellation.

layout using the force-directed algorithm and then gradually transform it so that it becomes close to the layout obtained using the centroidal Voronoi tessellation. In this section we briefly explain the force-directed formulation and centroidal Voronoi tessellation, which is followed by the proposed hybrid approach between the two network layout algorithms.

A. Force-Directed Algorithm

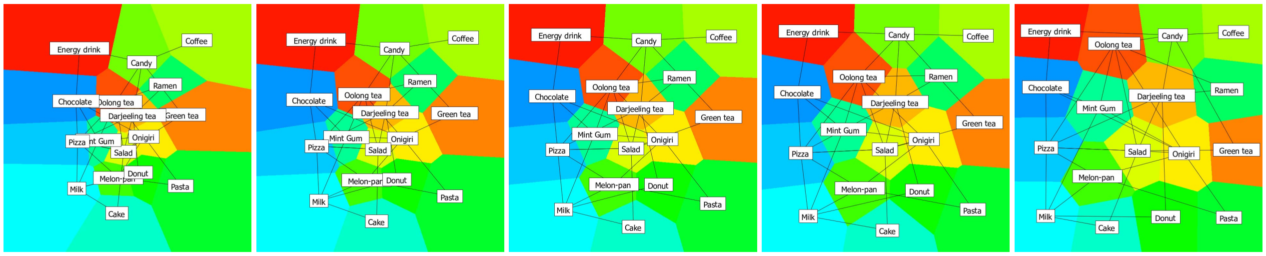
As an algorithm for producing the initial network layouts, we employed the conventional force-directed algorithm. Suppose that we have n network nodes $\boldsymbol{v}_0, \boldsymbol{v}_1, \ldots, \boldsymbol{v}_{n-1}$. In our approach, we introduced the force-directed model that simulates physical springs using the Hooke's law, which can be given by $F_d = k_d(|\boldsymbol{v}_i - \boldsymbol{v}_j| - l_0)$, where k_d represents the spring constant, l_0 is the original length of the spring, and $|\boldsymbol{v}_i - \boldsymbol{v}_j|$ is the Euclidean distance between the end nodes $\boldsymbol{v}_i$ and $\boldsymbol{v}_j$. In addition, k_d is the constant of the spring and set to be 1.0 by default. In this formulation, we applied this force to all the pairs of nodes that are connected by links.

Furthermore, we also assume that each node has an electrical charge and introduce repulsive forces between every pair of nodes as $F_r = -k_r/|\boldsymbol{v}_i - \boldsymbol{v}_j|^2$, where k_r corresponds to the electric force constant and set to be 0.1 by default. In summary, we compute the combinations of these drawing and repulsive forces to each network node as

$$F_s(\boldsymbol{v}_i) = \sum_{j \in N_i} k_d(|\boldsymbol{v}_i - \boldsymbol{v}_j| - l_0)(\boldsymbol{v}_j - \boldsymbol{v}_i) - \sum_{k \in V - \{i\}} \frac{k_r(\boldsymbol{v}_k - \boldsymbol{v}_i)}{|\boldsymbol{v}_i - \boldsymbol{v}_k|^2}, \quad (1)$$

where N_i is an index set of nodes adjacent to $\boldsymbol{v}_i$ and $V - \{i\}$ is an index set of all the nodes excluding $\boldsymbol{v}_i$. We exert this force to each node until we can obtain the equilibrium layout of the network, where we can empirically generate a visually plausible layout that avoids excessive visual clutter.

Nonetheless, simply applying this formulation cannot fully facilitate us to avoid overlaps among the nodes if



(a) (b) (c) (d) (e)

Figure 3. Transition from the force-directed layout to that of centroidal Voronoi tessellation. (a) $\alpha = 0.1$. (b) $\alpha = 0.3$. (c) $\alpha = 0.5$. (d) $\alpha = 0.7$. (e) $\alpha = 0.9$. Here, $(1 - \alpha)$ and α represents the weights of the force-directed algorithm and centroidal Voronoi tessellation.

they are associated with rectangular text labels as shown in Figure 2(a). In our approach, we use this layout as a starting point for further exploring optimized layouts of such an annotated network.

B. *Centroidal Voronoi Tessellation*

Centroidal Voronoi tessellation is an effective means of uniformly distributing seed points within a finite domain, and thus can potentially alleviate unwanted overlaps among node labels. For computing the centroidal Voronoi tessellation, we repeat the following three steps until we reach the stable partitioning of the domain:

1) Compute the Voronoi tessellation with seed points,
2) Identify the barycenter of each Voronoi cell, and
3) Move a seed point to its corresponding barycenter.

In Step 1), we compute the Voronoi tessellation by referring to the coordinates of each node $\boldsymbol{v}_i$ as a seed point. For composing the Voronoi diagram, we employed a hardware-assisted algorithm [16] for faster computation, where we place 3D cones centered at the given seed points in different colors, and project them from the top. We then compute the barycenter of each Voronoi cell for $\boldsymbol{v}_i$ as $\boldsymbol{g}(\boldsymbol{v}_i)$ in Step 2). This is accomplished by scanning the frame buffer to collect a set of pixels of the same color for each Voronoi cell, and computing the barycenter as the average of the corresponding pixel coordinates. In Step 3), we move each seed point $\boldsymbol{v}_i$ to the barycenter of the corresponding Voronoi cell $\boldsymbol{g}(\boldsymbol{v}_i)$ to uniformly distribute the network nodes. This amounts to applying the following force to each node $\boldsymbol{v}_i$ as

$$F_v(\boldsymbol{v}_i) = C(\boldsymbol{g}(\boldsymbol{v}_i) - \boldsymbol{v}_i), \tag{2}$$

where C indicates a constant that control the strength of this force and set to be 10 by default in our implementation.

We continue to take these three steps until each seed point (i.e. network node) reaches its equilibrium position. Figure 2(b) shows an example where the network nodes together with their labels are displaced using the centroidal Voronoi tessellation.

C. *Hybrid approach*

As shown in Figure 2(a), the conventional force-directed algorithm can successfully alleviate visual clutter while it cannot explicitly spare sufficient space around the network nodes. Thus the associated node labels may overlap with each other if the network is excessively dense. On the other hand, the centroidal Voronoi tessellation facilitates us to uniformly distribute the network nodes, although it cannot fully eliminate visual clutter including edge overlaps as shown in Figure 2(b). Thus, our challenge here is to seek a plausible compromise between the two layouts, which is accomplished by smoothly transforming the initial force-directed layout to that based on centroidal Voronoi tessellation.

In our approach, we accomplish this goal by applying to each node $\boldsymbol{v}_i$, the weighted sum of the forces exerted by the two algorithms (cf. Eq. (1) and (2)) as:

$$F_h(\boldsymbol{v}_i) = (1 - \alpha)F_s(\boldsymbol{v}_i) + \alpha F_v(\boldsymbol{v}_i). \tag{3}$$

where α is the blending ratio between the two forces. Furthermore, for maximally retain the spatial layout obtained through the force-directed algorithm, we start with $\alpha = 0$ and then gradually increase it so that we can smoothly transform the initial layout to that of centroidal Voronoi tessellation. This is accomplished by computing the total sum of the forces in Eq. (3) every time when we displace the network nodes, and updates the weights by a small amount δ when the sum becomes less than a predefined threshold. Here, δ is set to be 0.02 by default in our approach. This allows us to respect the original layout of the network while sparing more space around the nodes for their annotations.

Figure 3 shows how we can transform the initial network layout by incorporating the influence of the centroidal Voronoi tessellation, where the overlaps among the network nodes are gradually resolved during the transition while respecting the relative positions of the network nodes in the original layout. In our approach, we first increase α to 0.6 and further increase it up to 0.9 if we still have overlaps among node labels in the network. This also helps us avoid unwanted edge overlaps, which often arise from the layout based on the centroidal Voronoi tessellation as shown in Figure 2(b).

IV. Enhancements for Interactive Environments

This section explains several enhancements of our approach especially for better use in interactive environments.

(a) (b) (c)

Figure 4. Network layouts based on centroidal Voronoi tessellation with (a) the Manhattan distance, (b) Chebyshev distance and (c) its anisotropic version.

A. Choice of the distance metric

Since annotation labels associated with the network nodes are rectangular in general, we can employ anisotropic distance metrics for better placement of node labels. Here, we tested the Manhattan and Chebyshev distances.

The Manhattan distance between the two nodes $\boldsymbol{v}_i = (x_i, y_i)$ and $\boldsymbol{v}_j = (x_j, y_j)$ is defined as

$$d(\boldsymbol{v}_i, \boldsymbol{v}_j) = |x_1 - x_2| + |y_1 - y_2|. \quad (4)$$

This can be easily calculated by placing 3D square pyramids instead of cones in the algorithm for Voronoi partitioning [16], where the sides of each square basement should be aligned with diagonal directions in the screen space.

On the other hand, the Chebyshev distance between the two nodes $\boldsymbol{v}_i$ and $\boldsymbol{v}_j$ is defined as

$$d(\boldsymbol{v}_i, \boldsymbol{v}_j) = \max(|x_1 - x_2|, |y_1 - y_2|). \quad (5)$$

This is again readily implemented by placing 3D square pyramids in generating Voronoi tessellation while this time the sides of each square basement should be aligned with horizontal and vertical directions.

Figure 4 exhibits the comparison between the layouts based on these two distance metrics. In Figure 4(a), text annotation labels with the network nodes are bounded by diamond-like shapes while they are enclosed by box-like shapes in Figure 4(b). Because annotation labels for the nodes are basically rectangular, we employed the Chebyshev distance for partitioning the screen space.

B. Distance Anisotropy in Sparing Labeling Space

We can observe from the network layout in Figure 4(b) that the text label “Darjeeling tea” exceeds the boundary of the corresponding Voronoi cell. This is because this annotation label contains a large number of letters and thus is horizontally wide as compared with other labels. This leads us to the idea of adaptively changing the aspect ratio of such Voronoi cells by incorporating an appropriate anisotropic distance. One of the simple solutions is to modify the definition of the Chebyshev distance metric as

$$d(\boldsymbol{v}_i, \boldsymbol{v}_j) = \max(|x_1 - x_2|, \alpha|y_1 - y_2|), \quad (6)$$

where α represents the global aspect ratio of the horizontal distance with respect to the vertical distance. Nonetheless, we cannot locally modify the aspect ratio according to the size of the text label associated with each node.

What we actually did in our approach is to scale the square basement of the pyramid when generating the Voronoi tessellation, so that the basement of each node becomes horizontally wide according to the aspect ratio of the corresponding text label. This allows us to adaptively adjust the size of the Voronoi cells by counting the number of letters in the text annotation. Figure 4(c) shows the centroidal Voronoi tessellation with the anisotropic version of the Chebyshev distance, where we can easily confirm that the underlying Voronoi cells can effectively accommodate text labels.

C. Selective Annotation of Network Nodes

As mentioned earlier, our approach allows users to interactively annotate individual nodes even while optimizing the network layout. This interactive editing is supported by a picking interface for freely dragging an individual network node and a rubber-band interface for selecting a subset of nodes to be annotated. Together with the capability of zooming the network layout, our approach can fully facilitate visualization of large-scale networks within the limited screen space.

V. Experimental Results

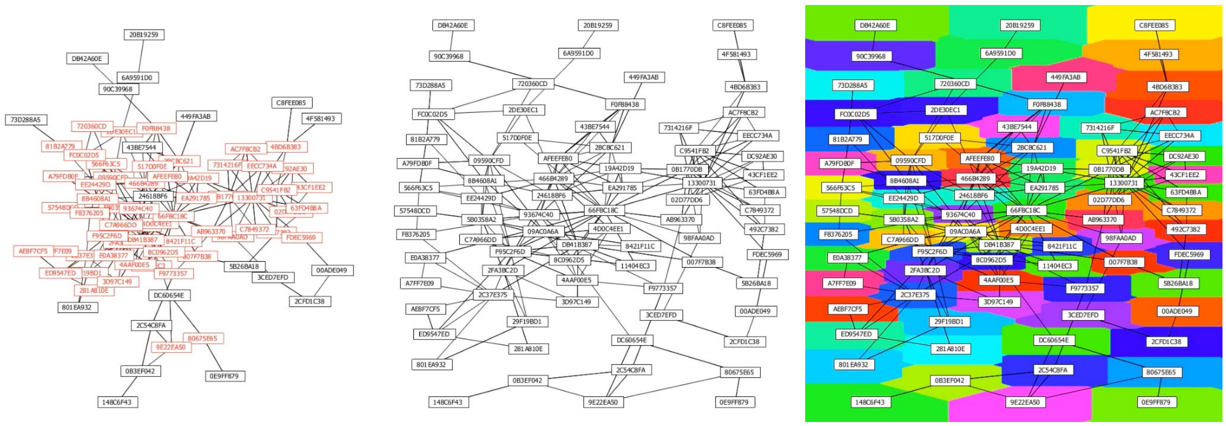
Our prototype system has been implemented on a desktop PC with 3.5 GHz 6-Core Intel Xeon E5 CPU and 32GB RAM. The source code was written in C++ using OpenGL for graphics rendering and Qt for interface. We also employed network datasets provided by the Graphviz project (http://www.graphviz.org/) as examples in our experiments.

Throughout this section, we compute the sum of overlap areas between all the pairs of labels assigned to $\boldsymbol{v}_i$ and $\boldsymbol{v}_j$, where $i, j \in V$ and $i \neq j$. This is accomplished by calculating the width w_{ij} and height h_{ij} of the rectangular area shared by the labels of $\boldsymbol{v}_i$ and $\boldsymbol{v}_j$, which are given by:

$$w_{ij} = \max\{0, \min\{w_i + w_j - |x_{ij}|, w_i, w_j\}\}, \quad (7)$$
$$h_{ij} = \max\{0, \min\{h_i + h_j - |y_{ij}|, h_i, h_j\}\}. \quad (8)$$

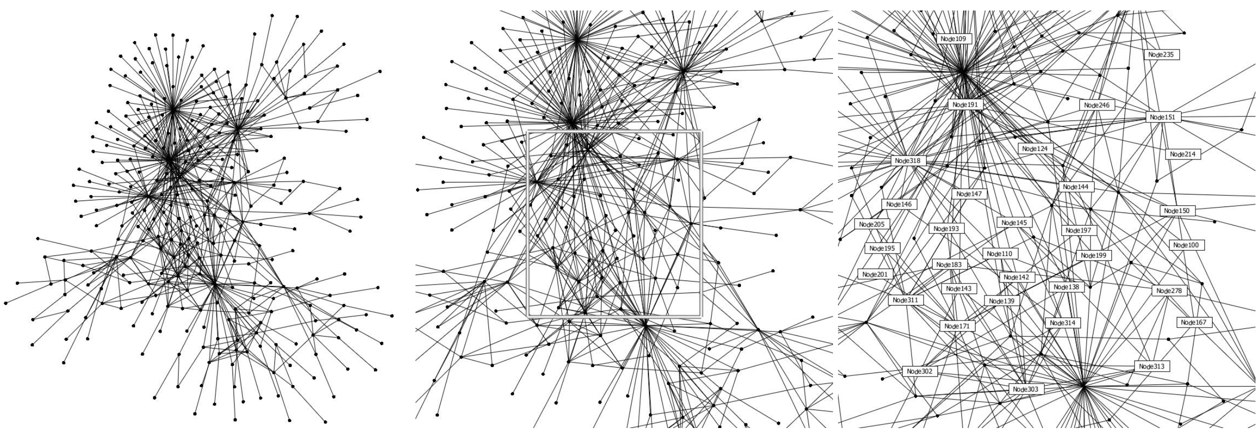
Note that x_{ij} and y_{ij} are the x- and y-coordinates of the vector from $\boldsymbol{v}_i$ to $\boldsymbol{v}_j$, and w_i and h_i represent the width and height of the annotation label assigned to $\boldsymbol{v}_i$, respectively. We define the summation of $w_{ij} \cdot h_{ij}$ for all the pairs of nodes $\boldsymbol{v}_i$ and $\boldsymbol{v}_j$ as the degree of overlap among the node labels, and also highlight the labels having overlaps in red within our experimental results. Note that the area of the window is fixed to 16.0 in our setup.

Figure 5 shows layouts of the medium-sized network called “b124” ($|V| = 79, |E| = 281$). The conventional force-directed algorithm provides us with a network layout that cannot explicitly avoid overlaps among the node labels (Figure 5(a)). Compared with this result, our approach



(a) (b) (c)

Figure 5. Visualizing the "b124" network data ($|V| = 79, |E| = 281$). (a) A layout obtained using the force-directed algorithm. The total area of label overlaps is 1.47234. (b) A layout obtained using our approach. We can completely eliminate overlaps among the node labels when we increase α up to 0.84. (c) The associated Voronoi tessellation where each cell is rendered in a difference color.



(a) (b) (c)

Figure 6. Visualizing the "b102" network data ($|V| = 302, |E| = 611$). (a) A initial layout obtained using the force-directed algorithm. (b) Select a subset of nodes by closing them with a rubber-band using our interface. (c) An updated layout of the network where the selected nodes are annotated with text labels.

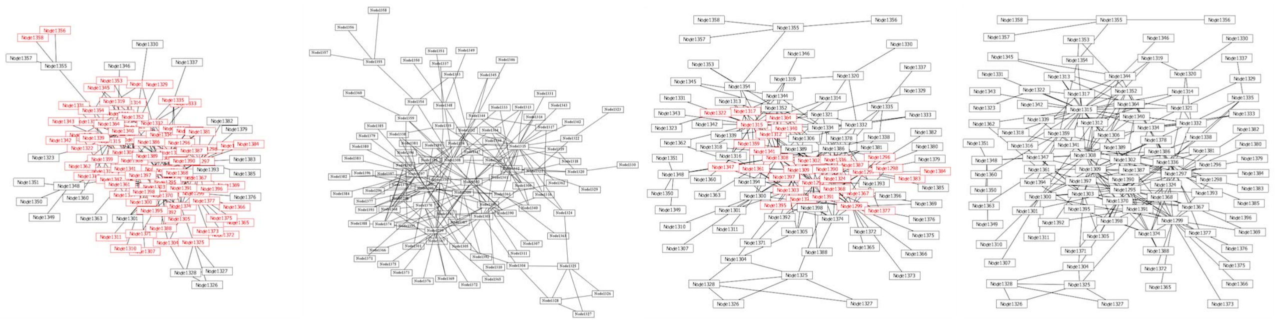
improves the network layout together with more balanced distribution of node labels (Figure 5(b)), by seeking a good compromise between the force-directed algorithm and centroidal Voronoi tessellation (Figure 5(c)).

The interface of our system facilitates us to selectively annotate the network nodes as shown in Figure 6. Suppose that we have an initial layout of the network data "b102" obtained using the conventional force-directed algorithm (Figure 6(a)). We can select a subset of nodes to be annotated by using a rubber-band interface (Figure 6(b)) and then search for an visually plausible layout of the selected node labels using our approach (Figure 6(c)).

We also compared our approach with the previous algorithm by Gansner et al. [5], where they spare the labeling space around each node while faithfully retaining the original spatial layout of the network. Figure 7 shows such an example where we employed the "b106" network data as an example. Starting from the initial layout based on the conventional force-directed algorithm (Figure 7(a)), the algorithm by Gansner et al. inserts the additional space for placing text labels and thus cannot explicitly maximize the space coverage of the screen space (Figure 7(b)). However, our approach composes a more compact layout of the node labels by incorporating the centroidal Voronoi tessellation with the anisotropic distance metric. Our algorithm first increases the blending ratio α to 0.6 (Figure 7(c)) and further augments it to 0.9 so that we can resolve all the possible overlaps among annotation labels (Figure 7(d))).

VI. Conclusion

This paper has presented an approach to laying out annotated networks while maximally eliminating overlaps among



(a) (b) (c) (d)

Figure 7. Visualizing the "b106" network data ($|V| = 104, |E| = 203$). (a) A layout obtained using the force-directed algorithm. The total area of label overlaps is 2.55528. (b) A layout obtained using the algorithm proposed by Gansner et al. [5]. Label overlaps are complete eliminated. (c) A layout obtained using our approach when we increase the blending ratio α up to 0.6. The total area of label overlaps is 0.276022. (d) A layout obtained using our approach when we increase α to 0.9 for completely eliminating label overlaps.

the node labels especially in interactive environments. Our idea is to seek a plausible compromise between the layouts obtained using the conventional force-directed algorithm and centroidal Voronoi tessellation. Furthermore, we also incorporated a specific type of anisotropic Chebyshev distance metric to make the resulting label placement as compact as possible. Several experimental results together with the comparison with the previous technique are presented to demonstrate the feasibility of our approach.

Our future extensions include extending our approach to directly visualize larger-scale network datasets. Sophisticating the interface for editing the layout of annotated network is also left as our future work.

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