Comprehensive and Accessible Channel Routing for Microfluidic Devices

Gerold Fink*, Philipp Ebner* and Robert Wille*†
*Johannes Kepler University - Institute for Integrated Circuits, Linz, Austria
†Software Competence Center Hagenberg GmbH (SCCH), Hagenberg, Austria
{gerold.fink, philipp.ebner, robert.wille}@jku.at
https://iic.jku.at/eda/research/microfluidics

***Abstract*—Microfluidics is an emerging field that allows to minimize, integrate, and automate processes that are usually conducted with unwieldy laboratory equipment inside a single device; resulting in so-called "Labs-on-a-Chip" (LoCs). The design process of channel-based LoCs is still mainly conducted manually thus far – resulting in time-consuming tasks and error-prone designs. This also holds for the routing process, where multiple components inside an LoC should be connected according to a specification. In this work, we present a routing tool which considers the particular requirements of microfluidic applications and automates the routing process. In order to make the tool more accessible (even to users with little to no EDA-expertise), it is incorporated into a user-friendly and intuitive online interface.**

***Index Terms*—microfluidics, routing, channel-based, matching-length, rubber-band**

I. Introduction

Microfluidics is an emerging field that covers the behavior of fluids at small scales (typically ranging from micro- to pico-liters [1]). This resulted in microfluidic systems that are able to replace bulky and expensive laboratory equipment by minimizing, integrating, and automating processes on a single chip. Corresponding systems are therefore called "Labs-on-a-Chip" (LoCs) that allow to conduct a broad range of (bio-)chemical experiments and, thus, found great applications in medicine, biology, chemistry, etc. [2]–[4]. Despite their broad applications, the design process of LoCs is still in its infancy and mostly done by hand. Various design automation methods have been proposed that aim to help designers during different tasks of the whole design process [5]–[10].

One of these design tasks is commonly known as *routing*, where usually multiple components and input/output ports have to be connected inside a microfluidic chip while, at the same time, certain constraints must be considered. For example, flow-based devices which are controlled by micro-valves have a two-layer architecture, where a routing method is required for the control-layer [11] (that operates the valves) as well as the flow-layer [12] (that consists of the actual channels to transport the samples). Other channel-based platforms such as droplet-based [13], paper-based [14], or capillary-based [15] microfluidic devices have similar routing challenges, although they only have a single flow-layer.

An obvious approach to automate this task is, of course, to take inspirations from methods proposed for the electrical domain such as wire routing solutions for printed circuit boards (PCBs) [16] or integrated circuits (ICs) [17]. However, these methods usually yield layouts with cornered channel bends (90°) which are not ideal for the transportation of fluids, since they can affect the flow inside the channel [18], [19]. Moreover, such routers [12], [20] usually aim for connections with minimal length while, in microfluidics, the channels are frequently subject to further constraints, e.g., on their length to ensure a specific hydrodynamic resistance, a maximal/minimal flow rate, a certain time a fluid needs to pass a channel, etc.

Because of these shortcomings, it is paramount to have dedicated solutions for channel routing on microfluidic devices that *explicitly* satisfy these domain-specific requirements. Contributions in this direction were made in [19], [21], addressing the problems of cornered channel bends and length matching constraints – but only individually. However, realizing a solution that addresses *both* issues at the same time is considerably harder to achieve. Additionally, due to missing interfaces and a procedure that still heavily relies on design automation expertise, these routing algorithms did not get established in the microfluidic community thus far.

In this work, we propose a *comprehensive* and *easily accessible* solution to this problem. More precisely, we present a tool that determines the desired routings and, at the same time, satisfies different domain-specific constraints (such as corners with a predefined minimal bend radius or constraints impacting the lengths of the channel and, by this, also the hydrodynamic resistance, flow rate, timing, etc.). Additionally, the tool is incorporated into a front-end which also allows users with little to no EDA-experience to obtain corresponding results.

The remainder of this work is structured as follows: First, we go into more detail of the considered routing problem in the next section. Then, the resulting tool and its applicability is presented in Sec. III. Finally, the paper is concluded in Sec. IV.

II. Considered Problem

In this section, we describe the considered problem in more detail and discuss the challenges that come along with it. To this end, we use Fig. 1 that provides a corresponding illustration of the problem we want to address.

More precisely, in the considered scenario different components are placed on a 2D-layer, which are supposed to perform different microfluidic operations such as mixing, heating, incubation, etc. Each of these components has one or more inlets as well as outlets, through which fluids/droplets can enter or exit the component. Now, a typical design task is to connect these components as well as input/output ports of the chip in a certain way (based on a corresponding specification), e.g., to guide fluids/droplets through the chip and, by this, realize a desired experiment – constituting a *routing* problem.

In the domain of conventional electronic circuits, routing is an established process for which numerous methods have been proposed, e.g., for PCBs [16] or ICs [17]. Accordingly, it seems obvious to simply use these methods as a basis for microfluidic devices as well. However, for channel-based microfluidic devices as considered in this work, these schemes do not properly work. Especially the following challenges constitute crucial problems:

Rounded Corners: In order to ensure a proper flow of the respective fluids, corners, i.e., changes in the direction of the

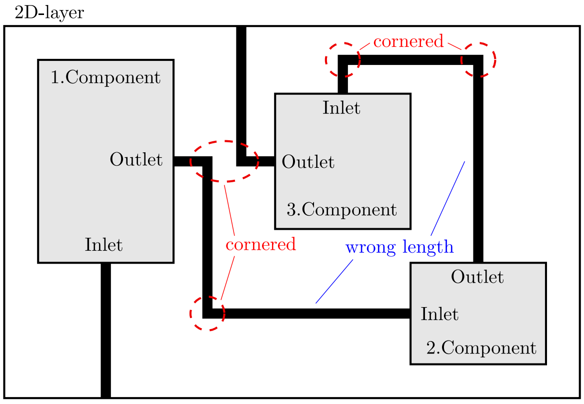


Fig. 1: Routing layout

channels, must be as smooth/round as possible – ideally with a certain bending radius. Methods inspired by conventional routing methods for electronic circuits rely on grid-based schemes and, hence, usually yield routing layouts with rather angular corners (also known as *Manhattan layouts*). Since they affect the flow inside the channels, they are not optimal for channel-based microfluidic devices.

Length Constraints: Frequently, channels in a microfluidic device are not only supposed to connect the different components but additionally must satisfy a desired length due to various constraints. Such constraints are, e.g., a specific hydrodynamic resistance, a maximal/minimal flow rate through the channel, a certain time a fluid/droplet needs to pass a channel, etc.

Example 1. *Let's assume we have the three components placed on a layout as shown in Fig. 1. Applying any method that is inspired by routing for electronic devices will result in a solution, where the corresponding in- and outlets are connected in an angular and direct fashion as shown in the figure. More precisely, all corners of the channels have angles of* $90°$ *and, hence, most certainly will disrupt the flow of the fluids inside them. Furthermore, while the connected channels are indeed correctly routed, they have more or less arbitrary lengths which can become critical in situations where a certain channel length is desired. Overall, the resulting routing most likely will not be feasible for microfluidics.*

Accessibility: Despite the fact that, thus far, no solution exists which *comprehensibly* addresses the requirements from above, accessibility is another huge problem when it comes to design automation for microfluidics. In fact, the vast majority of the solutions proposed in the past require a substantial programming or EDA-background (notable exceptions are, among others, [5]–[7]). Because of this, many design automation solutions, even if they generate great results, often do not get established in practice.

III. Proposed Tool

In order to overcome these issues, we implemented a routing tool that tackles the introduced challenges. In this section, we present the solution. This also includes an illustration of the usage of the tool as well as a discussion of the results that can be obtained by it.

A. Solution

The main approach of the routing method is based on a so-called rubber-band router [22], [23]. As the name suggests, a connected channel between two inlet/outlets is modeled as a rubber-band. This has the effect that, when an obstacle prevents a direct connection, the channel just bends around the obstacle as shown in Fig. 2a. Hence, this router method does *not* rely on common grid-based algorithms and, thus, can produce an "any-angle" layout.

Having that as the main concept, we solve the considered challenges as follows:

Addressing Rounded Corners: Critical points in the layout such as inlet/outlets or corners of obstacles are modeled as waypoints (marked as red circles in Fig. 2a). Channels must have a certain distance to these round waypoints and can only pass them by a circular path. This distance can be adjusted by adapting the radius of these waypoints. By this, a desired bending radius of the channel is guaranteed. As a result, a channel will always be a combination of straight segments and arcs when a straight connection is not possible. This finally prevents angular corners of common routing algorithms.

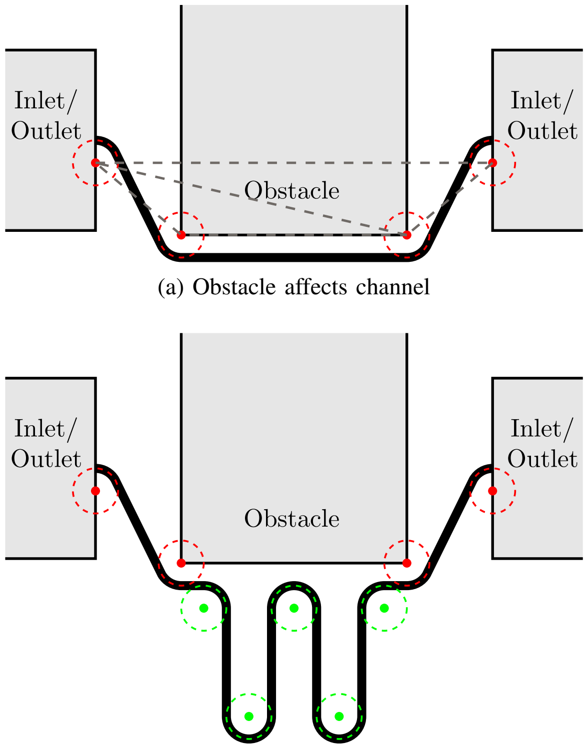
Addressing Length Constraints: When a channel should realize a desired length, a common concept in microfluidics is to add a meander structure to the channel. They allow to adjust the length of the channel while, at the same time, do not occupy too much space on the chip. In the proposed routing concept, such meander structures can be realized by placing additional waypoints (marked as green circles in Fig. 2b) at convenient spots near the corresponding channel. By adjusting the position of these extra waypoints, the desired channel length can be generated.

Addressing Accessibility: In order to make the router more accessible, the router is implemented as an online tool, which allows to open it directly inside a browser and prevents further installations processes. Moreover, the interface of the tool is designed such that also users with little to no programming or EDA-experience can interact with it easily, i.e., the tool is supposed to be well suited for microfluidic engineers. To this end, user inputs can either be made by drawing the corresponding components/obstacles/connections inside a drawing area, or by entering the corresponding information through user-friendly input masks. Additionally, instead of defining a desired length of a channel, the user is able to specify, e.g., a certain hydrodynamic resistance of a channel. This resistance will then be automatically converted to the corresponding length. Once all inputs are defined, a routing layout can then be generated in a push-button fashion and exported as a *Scalable Vector Graphics* (SVG) file.

B. Using the Tool

The resulting tool can be accessed by visiting https://iic.jku.at/eda/research/channel_router/. The tool particularly aims at microfluidic engineers looking for an efficient and easy-to-use solution to do the channel routing in their devices. The tool itself is shown in Fig. 3, which basically consists of a drawing and control area on the left- and right-hand side, respectively. The drawing area is the actual workspace of the tool and holds a visual representation of the current layout, while the control area contains buttons to start or clear the routing as well as an input mask to have a more detailed control over the specified layout. By clicking on the corresponding buttons inside the control area, the user can add the following two objects to the drawing area:

Components represent the actual building blocks on a microfluidic chip and cannot be crossed by a channel, i.e., they also serve as obstacles inside the layout. The tool allows to define these components in the form of n-gons (i.e., polygons with n sides). This has the advantage that rather complex objects can be created. To this end, the polygons can be directly



(a) Obstacle affects channel

(b) Additional waypoints for meander structure

Fig. 2: General idea of the proposed rubber-band routing

drawn inside the drawing area as shown in Fig. 3: Here, the top-left component is currently selected and, hence, its corners can be freely dragged around in order to represent the desired shape. Additionally, components can also be specified as a list of points and their corresponding x and y positions in order to allow for a more precise control over the exact shape and position.

Connections represent the inlets/outlets of components that should be connected inside a microfluidic chip. Hence, a single connection is basically a pair of two points that define the start and end point of a channel. A connection can also be easily added by directly drawing the start and end point (i.e., the inlets/outlets) on the boundary of corresponding components inside the drawing area, as shown in Fig. 3. Usually, the direction of a channel at the start and end point are perpendicular to the edge of the corresponding component, but the direction can also be defined manually by adjusting the second (smaller and darker) point near the start and end point of the connection. Moreover, when a new connection is added, the user is prompted to provide the desired channel width, the minimal space between two channels, the minimal bending radius, as well as an (optional) length of the channel (as shown on the right-hand side of Fig. 3). Note that, alternatively to the channel length, the hydrodynamic resistance of the channel can also be provided (in this case also the height of the channel, and the viscosity of the fluid have to be specified). The tool then automatically calculates the correspondingly needed length based on these parameters. Again, all these parameters as well as the coordinates and the start and end points can also be specified directly inside an input mask for a more precise control over the connection.

Once all these objects are defined, the user can start the routing process by pushing the “Route” button.

C. Results of the Tool

In order to illustrate a result generated by the tool, assume the user has entered a layout as illustrated in Fig. 3. Additionally, assume that the user specified the connections A, B, C to have a channel width of $w = 100\,\mu\mathrm{m}$, a minimal bending radius of $r = 100\,\mu\mathrm{m}$, and a minimal spacing of $s = 50\,\mu\mathrm{m}$, while the values for the connections D and E have been specified as $w = 150\,\mu\mathrm{m}$, $r = 150\,\mu\mathrm{m}$, and $s = 50\,\mu\mathrm{m}$. Moreover, assume the user specified that the connection B should have a particular length of $l = 5000\,\mu\mathrm{m}$, while the connection D should realize a hydrodynamic resistance $R_D = 3 \times 10^{12}\,\mathrm{kg}/(\mathrm{m}^4\mathrm{s})$ (with a channel height of $h = 50\,\mu\mathrm{m}$ and a fluid viscosity of $\mu = 1 \times 10^{-3}\,\mathrm{kg}/(\mathrm{ms})$).

Then, after clicking on the “Route” button, the tool instantly generates a layout and displays it to the user as shown in Fig. 4. As can be seen, all channels were routed correctly with respect to the specified parameters and no cornered angles where produced. Moreover, the router automatically generated corresponding meander structures inside the channels B and D in order to match the defined length and hydrodynamic resistance, respectively. In case of the connection B, the router even placed the meander in such a way, that the channel does not cross the obstacle in the middle of the layout. Having that, the user can now download a corresponding *Scalable Vector Graphics* (SVG) file in order to use it for further production processes.

D. Discussion

While the subsections above provided an intuition about the usage of and the results from the tool, we aim to complete this section with a discussion on the overall performance and applicability of the proposed method and resulting tool (covering what the method/tool is able to deliver, but also what it cannot provide yet).

The performance of the algorithm seems to be good. Even after considering dozens of different cases (inspired by real-world instances), the tool was able to generate valid results in negligible run-time. However, it might happen that the algorithm cannot determine a solution at all. In fact, after all, the method is not complete, i.e., can eventually not prove whether a solution exists. While this is one of the reasons for the efficient run-time performance (being complete would require a much larger search space traverse), this might look like a serious disadvantage at the first glance. However, if the method returns with no result, it is usually sufficient to slightly re-arrange the components and re-run the tool. After all, we were always able to eventually determine a result after such small re-arrangements. Since this did not harm the design task nor the validity of the solution, the proposed tool remained efficient.

IV. Conclusion

In this work, we presented a routing tool for channel-based microfluidic devices, i.e., devices where components must be connected by channels according to a certain specification. Current routing algorithms frequently do not fulfill the requirements needed in microfluidics, such as a minimal bending radius for channel bends or a length constraint for particular channels. Moreover, the accessibility of these routers is focused on users with an EDA-background, but are mostly not suitable for designers of microfluidic devices. The presented tool addresses these shortcomings. The tool can be accessed by visiting https://iic.jku.at/eda/research/channel_router/.

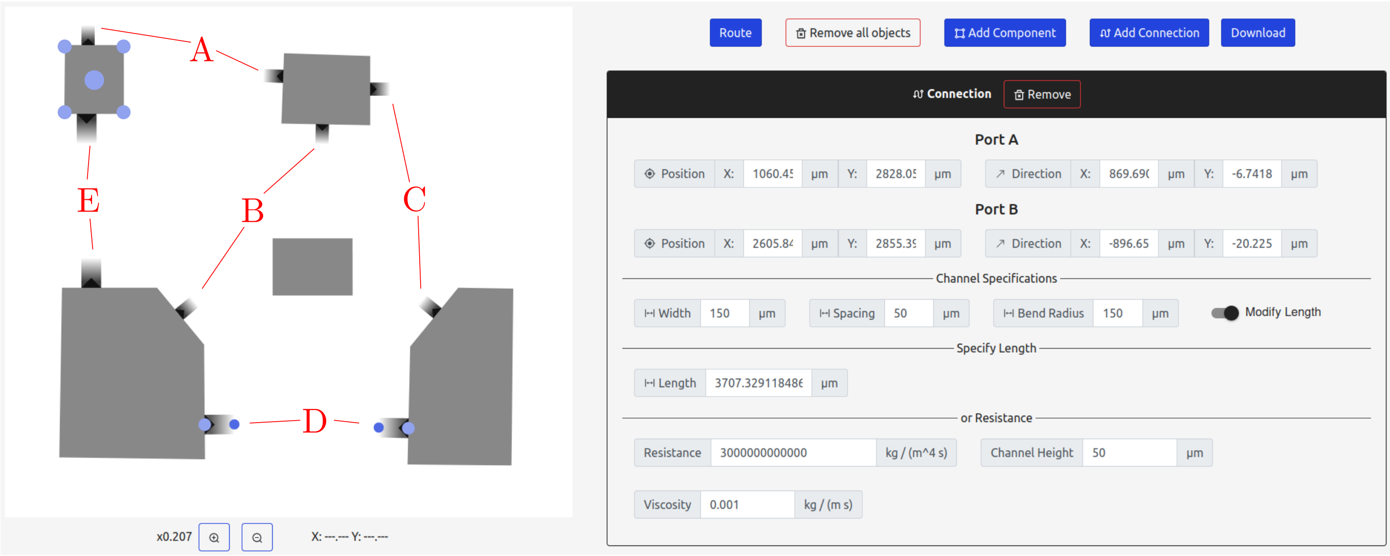


Fig. 3: Resulting online tool with drawing area (left) and control area (right)

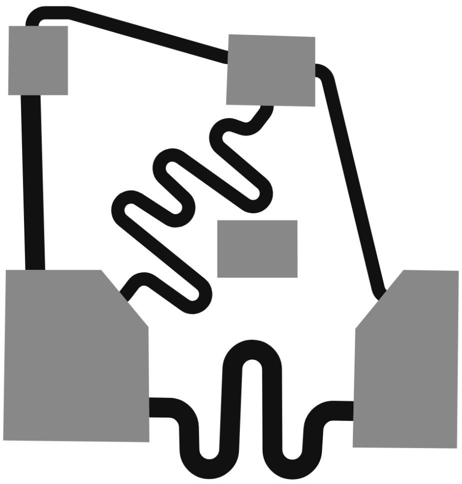


Fig. 4: Generated routing layout

Acknowledgments

This work has partially been supported by the FFG project AUTOMATE (project number: 890068) as well as by BMK, BMDW, and the State of Upper Austria in the frame of the COMET Programme managed by FFG.

References

[1] G. M. Whitesides, "The origins and the future of microfluidics," *Nature*, vol. 442, no. 7101, pp. 368–373, 2006.

[2] D. Mark, S. Haeberle, G. Roth, F. von Stetten, and R. Zengerle, "Microfluidic Lab-on-a-Chip platforms: requirements, characteristics and applications," *Chemical Society Reviews*, vol. 39, no. 3, pp. 1153–1182, 2010.

[3] P. S. Dittrich and A. Manz, "Lab-on-a-chip: microfluidics in drug discovery," *Nature Reviews Drug Discovery*, vol. 5, no. 3, p. 210, 2006.

[4] S.-Y. Teh, R. Lin, L.-H. Hung, and A. P. Lee, "Droplet microfluidics," *Lab on a Chip*, vol. 8, pp. 198–220, 2008.

[5] T.-M. Tseng, M. Li, D. N. Freitas, T. McAuley, B. Li, T.-Y. Ho, I. E. Araci, and U. Schlichtmann, "Columba 2.0: A co-layout synthesis tool for continuous-flow microfluidic biochips," *Trans. on Computer-Aided Design of Integrated Circuits and Systems*, vol. 37, no. 8, pp. 1588–1601, 2017.

[6] X. Huang, T.-Y. Ho, W. Guo, B. Li, and U. Schlichtmann, "Minicontrol: Synthesis of continuous-flow microfluidics with strictly constrained control ports," in *Design Automation Conference*. IEEE, 2019, pp. 1–6.

[7] A. Grimmer, P. Frank, P. Ebner, S. Häfner, A. Richter, and R. Wille, "Meander designer: Automatically generating meander channel designs," *Micromachines – Journal of Micro/Nano Sciences, Devices and Applications*, vol. 9, no. 12, 2018.

[8] A. Grimmer, W. Haselmayr, and R. Wille, "Automated dimensioning of Networked Labs-on-Chip," *Trans. on Computer-Aided Design of Integrated Circuits and Systems*, 2018.

[9] G. Fink, M. Hamidović, W. Haselmayr, and R. Wille, "Automatic design of droplet-based microfluidic ring networks," *Trans. on Computer-Aided Design of Integrated Circuits and Systems*, 2020.

[10] A. Grimmer, W. Haselmayr, and R. Wille, "Automatic droplet sequence generation for microfluidic networks with passive droplet routing," *Trans. on Computer-Aided Design of Integrated Circuits and Systems*, 2018.

[11] K. Hu, T. Dinh, T. Y. Ho, and K. Chakrabarty, "Control-layer routing and control-pin minimization for flow-based microfluidic biochips," *Trans. on Computer-Aided Design of Integrated Circuits and Systems*, vol. PP, no. 99, 2016.

[12] C.-X. Lin, C.-H. Liu, I.-C. Chen, D. Lee, and T.-Y. Ho, "An efficient bi-criteria flow channel routing algorithm for flow-based microfluidic biochips," in *Design Automation Conference*, 2014, pp. 1–6.

[13] X. Chen and C. L. Ren, "A microfluidic chip integrated with droplet generation, pairing, trapping, merging, mixing and releasing," *RSC Advances*, vol. 7, no. 27, pp. 16 738–16 750, 2017.

[14] X. Li, D. R. Ballerini, and W. Shen, "A perspective on paper-based microfluidics: Current status and future trends," *Biomicrofluidics*, vol. 6, no. 1, p. 011301, 2012.

[15] J. Guerrero, Y.-W. Chang, A. A. Fragkopoulos, and A. Fernandez-Nieves, "Capillary-based microfluidics—coflow, flow-focusing, electro-coflow, drops, jets, and instabilities," *Small*, vol. 16, no. 9, p. 1904344, 2020.

[16] A. Finch, K. Mackenzie, G. Balsdon, and G. Symonds, "A method for gridless routing of printed circuit boards," in *Design Automation Conference*. IEEE, 1985, pp. 509–515.

[17] C. Ababei, Y. Feng, B. Goplen, H. Mogal, T. Zhang, K. Bazargan, and S. Sapatnekar, "Placement and routing in 3d integrated circuits," *IEEE Design & Test of Computers*, vol. 22, no. 6, pp. 520–531, 2005.

[18] J. You, L. Flores, M. Packirisamy, and I. Stiharu, "Modeling the effect of channel bends on microfluidic flow," *IASME Trans*, vol. 1, no. 1, pp. 144–151, 2005.

[19] K. Yang, H. Yao, T.-Y. Ho, K. Xin, and Y. Cai, "Aarf: any-angle routing for flow-based microfluidic biochips," *Trans. on Computer-Aided Design of Integrated Circuits and Systems*, vol. 37, no. 12, pp. 3042–3055, 2018.

[20] A. Grimmer, Q. Wang, H. Yao, T.-Y. Ho, and R. Wille, "Close-to-optimal placement and routing for continuous-flow microfluidic biochips," in *Asia and South Pacific Design Automation Conference*, 2017, pp. 530–535.

[21] H. Yao, T.-Y. Ho, and Y. Cai, "PACOR: practical control-layer routing flow with length-matching constraint for flow-based microfluidic biochips," in *Design Automation Conference*, 2015, p. 142.

[22] D. Staepelaere, J. Jue, T. Dayan, and W.-M. Dai, "Surf: Rubber-band routing system for multichip modules," *IEEE Design & Test of Computers*, vol. 10, no. 4, pp. 18–26, 1993.

[23] T. Dayan, *Rubber-band based topological router*. University of California, Santa Cruz, 1997.