

Visualization of Self-Organizing Networks Operated by the ANR Algorithm

Ho Van Quan¹ Tobias Åström¹ Mikael Jern¹
¹National Center for Visual Analytics (NCVA)
Department of Science and Technology
University of Linköping, Sweden

¹{ho.van.quan, tobias.astrom, mikael.jern}@itn.liu.se

Johan Moe² Fredrik Gunnarsson² Harald Kallin²
²Wireless Access Networks
Ericsson Research
Ericsson AB, Sweden

²{johan.moe, fredrik.gunnarsson, harald.kallin}@ericsson.com

Abstract—Cellular radio networks are continually growing in both node count and complexity. It therefore becomes more and more difficult to manage the networks and necessary to use time and cost effective automatic computer algorithms to organize the network’s neighbor cell relations. Ericsson has developed such an algorithm, called Automatic Neighbor Relations (ANR), which solves a part of this problem by automatically creating and updating neighbor cell relation (NCR) lists, based on measured network data. Network operators need to have an understanding of the algorithm and of its reliability and performance, which is not easily perceived. This paper presents a visualization tool that visualizes the performance of ANR and gives the user a possibility to control it via policies. The tool allows the operators to follow the evolution of the network and to find problems occurring over time. In addition, it also supports finding potential problems that can occur in the future. The tool was evaluated by a group of relevant domain users and the results from the evaluation were highly positive.

Keywords: Network visualization, self-organizing network, multi-layer, multi-dimensional, time-varying, geospatial, large scale data, geovisual analytics

I. INTRODUCTION

In parallel with the 3G Long Term Evolution (LTE) specification and development [1, 2], the Next Generation Mobile Network (NGMN) association of operators brings forward requirements on management simplicity and cost efficiency [3]. The vision is that algorithms automate tasks that currently require significant manual efforts. One part of LTE that benefits from self-organization is automatic neighbor relation support. Ericsson has developed such an algorithm, called Automatic Neighbor Relations (ANR) [4], which automatically creates and updates neighbor cell relation (NCR) lists, based on measured network data. Furthermore, each cell is assigned physical cell identity (PCI), which is intended to be locally unique. The ambition is also to automatically reassign PCIs to avoid local conflicts. Network operators need to have trust in the reliability and efficiency of the algorithm and to be able to understand its behavior. To enhance confidence and understanding of the algorithm, we suggest that the algorithm should come with observation possibilities. For example, it must be possible to observe *the outcome*; what relations are added or removed, when in time this is happening etc. It must be also possible to understand *the algorithm behind*; why a cell changes its physical cell identity (PCI), how a PCI conflict is detected etc. For these purposes, visualization should be a useful approach to illustrate how the algorithm works and to support examining various aspects of the network.

Visual exploration and presentation of geospatial network data can provide analysts and operators with strategic and sometimes competitive advantage. Integrated

information and geovisualization methods, here referred to as geovisual analytics, focus on finding location-related patterns and relationship. Geovisual analytics tools are designed to support highly-interactive explorative spatial data analysis (ESDA) of large geospatial data. They enable analysts to look at geospatial data from multiple perspectives simultaneously and explore complex relationships that may exist over a wide array of spatial and multivariate scales. Geovisual analytics research focuses in particular on integrating cartographic approaches with visual representations and interactive methods from information visualization and ESDA [5, 6, 7, 8, 9] complementing human perceptual skills.

In this paper we introduce a visualization tool (named VoSON) that allows the operators to follow the evolution of the radio network under the operation of ANR. The tool is created in collaboration with Ericsson AB. It combines interactive visual displays, a multi-layer approach and the ability to work with multi-dimensional, time-varying, geospatial and large scale data sets.

The tool increases comprehension of a live network, and supports network examination by visualizing statistics and attributes of cells and cell relations over time. It further gives possibilities of filtering and high-lighting extreme values. A user easily finds explanations to problems by anomalies appearing as small distances between similar PCIs, long distances between cells and its neighbors, or a missing neighbor. With the tool, it is possible to examine and get further explanations to what caused the situation. If the user finds it necessary it is possible to control the algorithm directly within the tool.

The remainder of the paper is organized as follows. Section II gives an overview of related work. Section III presents the data description. Then the application is presented in section IV. In section V we present evaluation. Finally the conclusion is presented in section VI.

II. RELATED WORK

A. Visual exploration of spatial-temporal data

Visual exploration of spatial-temporal data has been the subject of many research papers, see [10] for an overview. Andrienko and Andrienko have illustrated several motivating approaches in earlier papers [6, 7]. Many papers [5, 11, 12], emphasize the advantages and need of multiple linked views (MLVs) for dynamically exploring time-varying, geographically referenced and multivariate attribute data and as a response a generic “GeoAnalytics” visualization (GAV) toolkit [13] was introduced and also employed in this case study. The extended parallel coordinates plot (PCP) in GAV with embedded statistical

filtering methods serves as a visual control panel linked to the choropleth maps [14] and is a central component in this project. GeoVista [15] and VIS-STAMP [16] are other examples of a general system with functionalities that supports ESDA tools that leverage visual and computational methods to search for space-time and multivariate patterns.

B. Communication network visualization

Communication network visualization is not new. There have been a lot of attempts to visualize the networks for various purposes as summarized in [17]. Most previous work on visualizing communication network data has been based on measuring performance or bandwidth characteristics. Some work is applied to network traffic monitoring, some is applied to intrusion detection and some is applied to network behavior monitoring.

Becker et al. [18, 19] presented the SeeNet environment that uses three graphical tools, ‘Link map’, ‘Node map’ and ‘Matrix display’ to visualize network data, analyze network traffic, and study overloads. Koutsofios et al. [20, 21] also introduced “SWIFT-3D that incorporates interactive 3D maps, statistical displays, network topology diagrams, and pixel-oriented displays for interactive exploration of large-scale network data. Nevertheless, in their work the networks are not self-organizing networks and their goals are also different from our goal therefore we are not sure their visualization techniques can well suit our needs. In our work we develop and use different visualization techniques such as cell maps, relation maps, PCPs, time sliders, time-graphs and various types of glyphs to serve our needs.

To our best knowledge, there has been no work published in literature that visualizes a self-organizing network to illustrate how an algorithm such as ANR operates the network.

III. DATA DESCRIPTION

We start by introducing a number of basic concepts in a radio network. In this context, a radio network includes three major objects: base station, its cells and cell relations. A base station is the physical entity with radio transmitters and receivers and constitutes one or more cells covering a geographical area. A cell supports mobility by knowing its close neighbors to which it can handover calls; i.e. cell relations. To help mobile terminals identify a cell, all cells broadcast two identifiers: a globally unique cell identifier (CGI) and a physical cell identity (PCI). CGIs are unique and constant over time but are more difficult and time consuming to detect for the mobile terminals. In contrast, PCIs are easier to detect but they are not unique since there are only 504 different PCIs in LTE. The PCI of a cell can vary over time since it needs to be unique in a region and may need to change.

In addition to physical properties, base stations, cells and cell relations have a number of performance properties as presented in the next part.

A. Data generation

To be able to visualize the performance of ANR, a data generator has been built to reflect the behavior of the algorithm. Before each simulation, a number of cells are prepared. In each interval of 15 minutes, the data generation script generates a number of mobiles in

handover locations between cells where the serving cell and target cell are determined from the radio conditions at the mobiles’ locations. Then events are recorded together with their time-stamp. The basic events include

- call drops
- handover successes or handover failures
- cell relations added or removed
- PCI conflicts detected, and
- PCI changes

Nevertheless, among the events above, only events such as PCI conflicts detected, PCI changes and relations added/removed are stored, as they reflect important changes in the network. Other events such as handover successes, handover failures or call drops are accumulated over each interval instead to save storage space. These events are therefore represented by statistics giving the number of occurrences of a specific event in an interval. In addition to these statistics, there are a number of other statistics computed from them. For example the numbers of incoming and outgoing handover failures are computed from the number of handover failures. The statistics are divided into two groups: cell statistics and cell relation statistics. The statistics such as the number of handovers dropped or the numbers of incoming and outgoing handover failures are cell statistics, and the statistics such as the number of successful or failed handovers are cell relation statistics. The statistics and events then are used to visualize for each time step to reflect the way the algorithm operates the network.

B. Simulation cases

To simulate the behavior of the algorithm we select the following three cases, each includes 225 cells prepared.

- In case 1 there is one PCI conflict between cell 210 and cell 225 (both use the same PCI 210). Furthermore, all cells that ideally would have both cells 210 and 225 in their neighbor cell list only have cell 225.
- In case 2 there is no PCI conflict, but there are only the most important neighbors in the neighbor cell lists.
- In case 3 there are only 15 PCIs initially assigned to cells by the following formula

$$PCI = ((Cell\ number - 1) \bmod 15) + 1$$

Furthermore, all cells are initiated with empty neighbor cell lists.

The simulation is done for one day that includes 96 intervals (or steps) of 15 minutes.

IV. APPLICATION

A. GAV Framework

To facilitate the development of VoSON we have used the GeoAnalytics Visualization (GAV) component toolkit [8] that allows for faster implementation as we can reuse several of the existing visual representations, dynamic linking and interaction tools in VoSON.

The GAV framework follows a human-centred approach enabling deployment of applications that puts the emphasis on tasks defined by the different domain expertise and needs of the target-groups. Each *atomic*

component according to its nature in the context of object-oriented programming performs a small specific user task in the overall GeoAnalytics process (figure 1). The higher-level *functional* component is constituted by the combination of one or more GAV *atomic* components together with user-defined components and typically implements the functionalities of a single view or a view integrated in a multiple-linked views application. Customizing the VoSON application, we have reused the functional component Parallel Coordinates Plot (PCP), and several atomic low-level components.

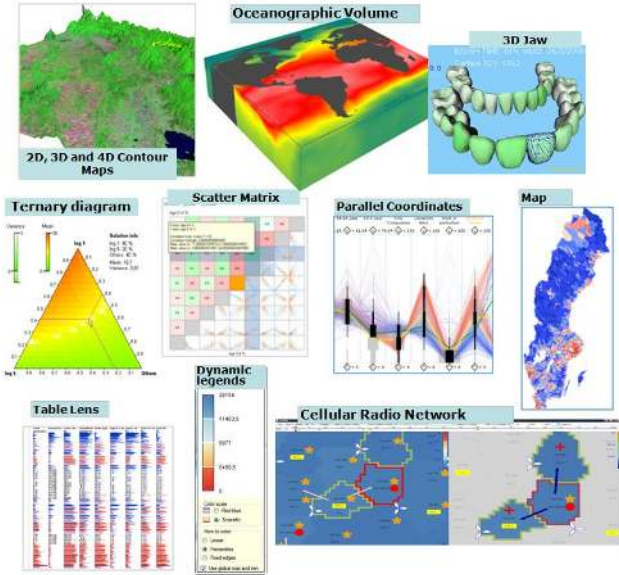


Figure 1. Example of some GAV functional components

Spatial-temporal and multi-dimensional data are effectively analyzed through the use of dynamically-linked views [11]. In order to detect complex patterns in cellular radio networks, it is convenient to view them through a number of different visual representations simultaneously, each of which is best suited to highlight different patterns and features. GAV facilitates an object-oriented architecture with compulsory components (selection manager and visibility manager etc.) and integrated with Visual Studio layout management provides alternative and different views of the cells and relations that can help stimulate the analytical visual thinking process so characteristic for geovisual analytical reasoning. The views are separated by interactive splitters allowing the user to scale the individual views and allocate more space to the visual representation that is most important. The views are coordinated using a data linking method based on the same data cube model and coloring scheme. Any statistical filtering or highlighting made in one of the linked functional components propagates to all the others via the selection manager.

B. Visualization of cells and relations

1) Visual representation of cells

Cells are common objects of a radio network. In order to enable efficient interaction with cells (for example selecting, highlighting, or marking) and presenting their data we need an appropriate way to represent them.

Cells have their geographical positions (the positions of antennas) and their own best-served areas, called coverage areas, as illustrated in the figure 2(a). Cell coverage areas

normally do not have a clear shape. Nevertheless, for the purpose of visualization of and interaction with them in this paper, an accurate representation of the coverage areas is not necessary. This fact suggests that cells can be represented as polygons that are approximations of their coverage areas. To accomplish this, a number of morphological operations on binary images such as removing isolated pixels, dilation and erosion are applied to simplify the coverage areas to polygons as illustrated in the figure 2(b).

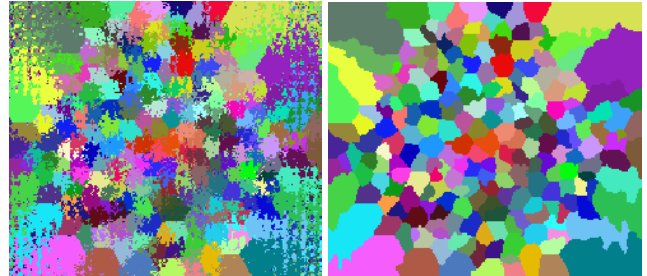


Figure 2. (a) cell coverage areas; (b) cell coverage areas simplified into polygons that allow easy interaction with cells

2) Using multi-borders and multi-subareas for presenting cell information

Each cell has a large number of attribute values and statistics, but can also include other types of information. For example, a cell can be selected as a serving-cell while highlighted as a target-cell, and marked as an extreme value cell. These things can occur at the same time, depending on how the user interacts with the cells (figure 3(b).) To be able to represent as much cell information as possible at the same time, we use a combination of multi-borders and multi-subareas of cells. Borders are computed from the main border of a cell and sub-areas are resulted from partitioning the cell area as illustrated in figure 3(a). The borders then are used for selecting and highlighting cells, and the main area and subareas are used for presenting multi-values of the cell and to mark the cell using colors, glyphs and texts as illustrated in figure 3(b). With two borders, one main area and twelve subareas, we can at the same time present fifteen pieces of information of cell through using colors, glyphs, and texts.

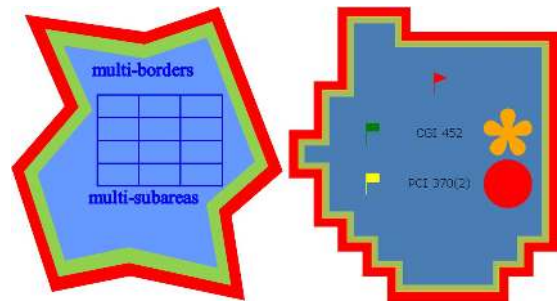


Figure 3. (a) an illustration of a polygon with multi-borders and multi-areas; (b) an illustration of using multi-borders and multi-sub areas for presenting various types of information of a cell. The red border represents a selected serving-cell. The less saturated yellow border represents a target-cell of a selected serving-cell. The red circle represents a cell changing PCI from the previous step. The orange flower represents a cell changing its relations from the previous step. The red flag represents a cell having an extreme value on a specific statistic in the current time step. The green flag represent a serving-cell of a relation having an extreme value on a specific statistic in the current time step. The yellow flag represent a target-cell of a relation having an extreme value on a specific statistic in the current time step. The texts present CGI and PCI of the cell in the current time step and cell PCI in the previous step if the cell changes its PCI from the previous step.

3) Visual representation of relations

A cell relation is a directed connection from a cell to other cell. An arrow is a simple and straightforward representation of this. It is, however, necessary to classify relations into a number of groups, for example newly added relations, removed relations, relations in black lists, relations being selected. To be able to represent these groups we use borders to highlight relations, glyphs and colors to represent different groups of relations as illustrated in figure 4 and 5.

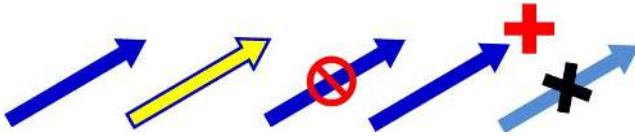


Figure 4. Arrows (with border) and glyphs are combined to represent different types of relations

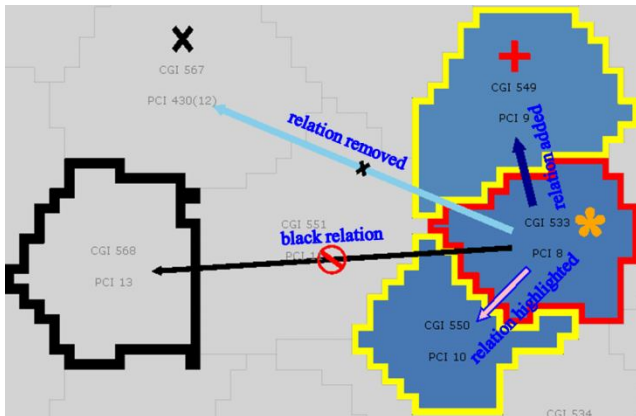


Figure 5. An illustration of using arrows together glyphs and colors to represent various types of relations

C. Multi-layer approach

At any moment network operators might want to see many different types of information of the network at the

same time. For example, they might want to see cells changing their PCIs from the last time step, and/or cells having new relations added, and/or cells having large numbers of call drops. Furthermore, they also want to control what information should be presented. To satisfy these needs, a multi-layer approach is suitable, and also supported by the GAV Framework. For each class of information there is a layer. These layers can be combined and controlled to be presented or hidden. A number of typical layers of the application are cell CGIs, cell PCIs, cells selected, cells changing their PCIs, cells changing their relations, cells with extreme values, PCI conflicts detected, relations in black lists, and relations added/removed.

D. Designing layout for visualization of cell and relation attributes

Cells and relations have many attributes and statistics that are time-varying. To display multiple attributes PCPs are good choices. Nevertheless, displaying all attributes and adding a time axis to display data for all time steps simultaneously would result in a PCP with very high data density. Instead we use combination of a PCP and an extra time graph. The PCP is to represent values of attributes/statistics at a time step and the extra time-graph is to represent changes of a selected attribute over time. Combining this and visual representation of cells and relations mentioned in section 4B, we suggest a layout including seven main views as follows (see figure 6):

- a context map, a cell-based PCP (PCC) and a cell graph that are used to visualize cells and cell data,
- a focus map, a relation-based PCP (PCR) and a relation graph that are used to visualize relations and relation data, and
- a time slider to control selection of time steps and to highlight important time steps.

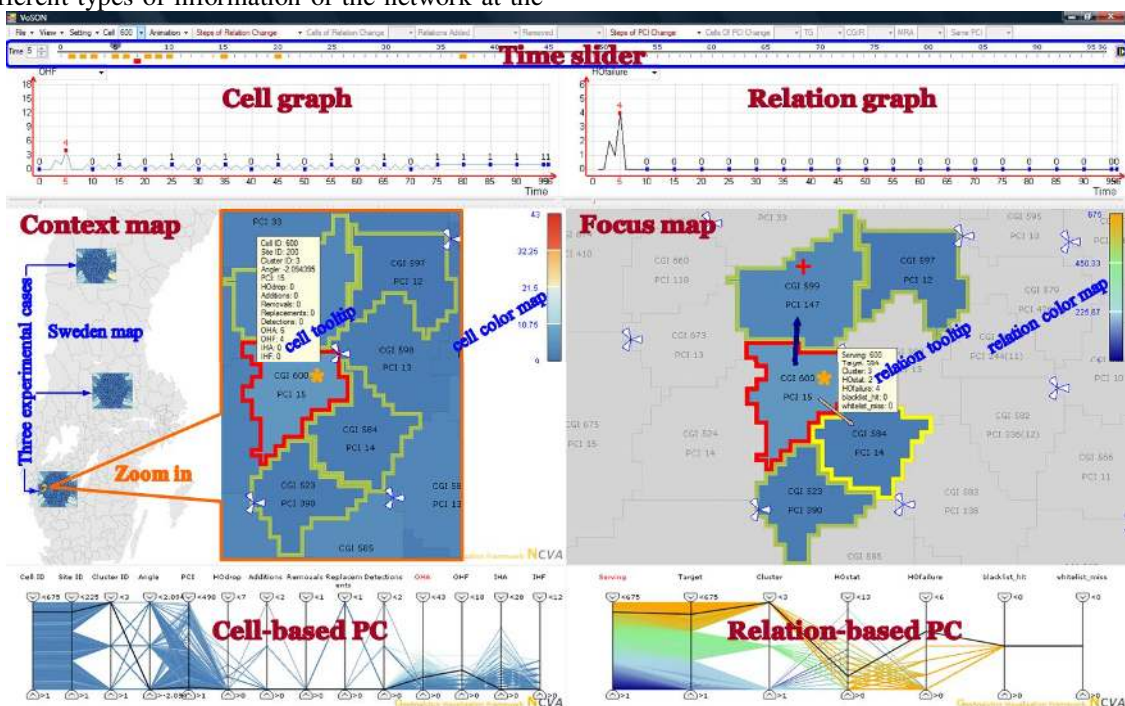


Figure 6. Main layout of the application. Two PCPs are used to visualize attributes for each time step; two graphs are used to visualize two attributes over time; two maps are used to visualize and interact with cells and relations; two color maps are used to color cells and relations; tooltips are used to display cell data and relation data; a time slider is used to move back and forth and visualize steps of changes of selected cells.

In detail, the context map is used to visualize and interact with cells, visualize events relating to cells such as cells changing PCI or PCI conflicts detected. It uses multi-subareas (mentioned above) to visualize a number of cell values and also uses a color map to color cell coverage areas according to the selected attribute/statistic in the PCC. A tooltip is also used to present cell data.

The focus map is used to visualize and interact with relations. It uses a color map to color relations according to the selected attribute/statistic in the PCR. A tooltip is also used to present relation data.

Two cell-based and relation-based PCPs are used to visualize cell attributes/statistics and relation attributes/statistics for each time step. Not all attributes/statistics of cells and cell relations are presented, only attributes/statistics selected by users are presented to save space. The PCPs are also used to filter cells and relations and to support finding extreme cells and relations.

The cell relation graph is used to visualize changes (in value) of an attribute/statistic of one or many cells over time and support finding problems. Similarly, the relation graph is used to visualize changes of an attribute/statistic of one or many relations over time and support finding problems.

The time slider is used to move back and forth and highlight time steps of change such as steps in which selected cells change their PCIs or add/remove relations.

E. Coordinated linked views

The views are dynamically linked to each other through selection and filtering. For example, when one or more cells are selected (through the cell combo-boxes on the menu bar or the context map or the PCC), the context map will highlight them and their neighbors with different

colors and levels of transparency; the PCC will also highlight these cells (but not their neighbors), and the cell graph will visualize values of a selected attribute of these cells over time. The focus map then will highlight and zoom in to these selected cells and their neighbors. Then only relations relating to the selected cells in the context map can be selected and interacted in the focus map. Similarly, when one or more relations are selected (through the focus map or the PCR), the context map will visualize them, the PCR will highlight them and the relation graph will visualize values of a selected attribute of these relations over time. If relations are selected by the PCC, then source-cells (or target-cells) of these relations will be selected and visualized in the three views related to cells. For filtering, when cells filtered in the PCC they will be immediately filtered in the context map.

F. Visualization of events and supervision of changes

There are various types of events happening in the network over time, such as cells adding new relations or removing relations, PCI conflicts detected, cells changing PCIs. Visualizing them as well as supervising changes of the network can help the operators see how the network evolves, answer various questions such as

- What relations are added or removed? When? Why?
- Which cells change their PCIs? When? Why?
- How are PCI conflicts detected?

and then get to understand how the algorithm works. To visualize events, we use the multi-layer approach in which each type of event is represented by a layer. These layers then can be presented or hidden according to the need of the operators. Figure 7 illustrates a number of events happening in step 10.

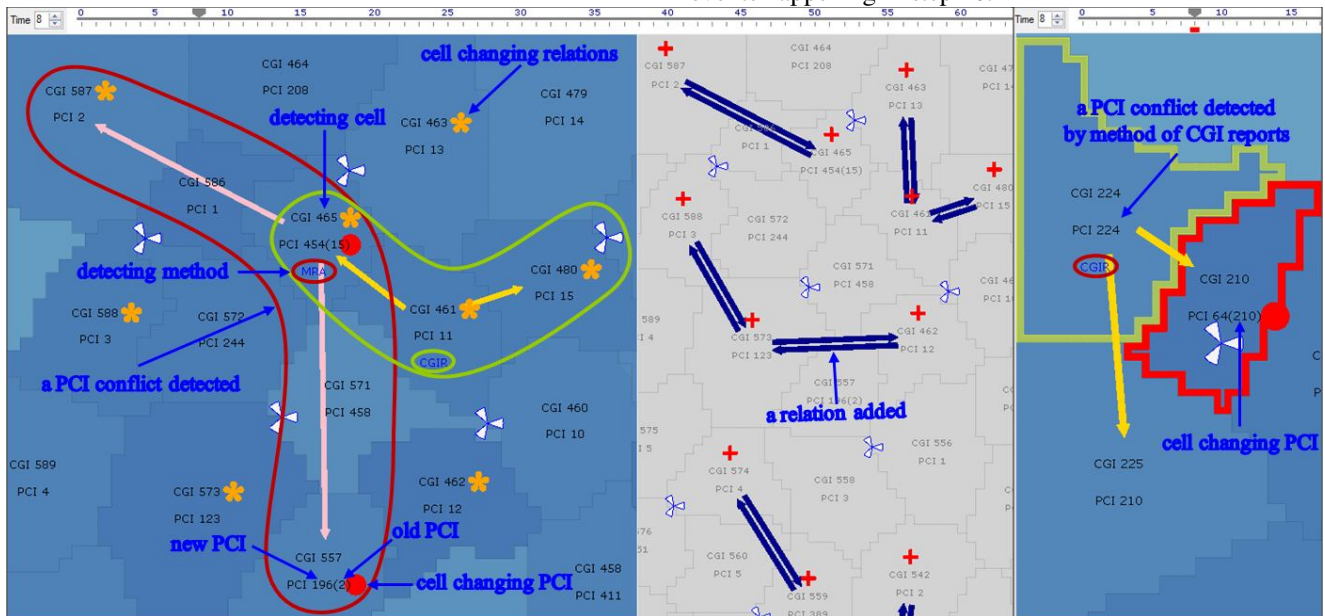


Figure 7. (left) an illustration of several events and changes happening in the case 3 in step 8. Cells changing their PCIs are marked by red circles; cells changing their relations are marked by orange flowers. New relations are highlighted and their target-cells are marked by 'plus' signs. PCI conflicts detected are represented by arrows (that go out from detecting cells) and the names of the detecting methods are displayed on the detecting cells; (right) a PCI conflict between cells 210 and 225 in the case 1 is detected in step 8 by cell 224 through the method of CGI reports.

To supervise changes happening in the network we uses two approaches. The first approach is to supervise changes of all elements happening in a time step. This approach can help answer questions such as where PCI conflicts are, which cells change their PCIs, which cells

add new relation. The second approach is to supervise changes happening over time of a group of elements selected. This approach can help answer questions such as when cells change their PCIs or when they add or remove relations (figure 8). The tool allows the users to supervise

changes in both ways. Figure 8 illustrates changes of cell 455 in step 5 and marks steps in which the cell changes its

PCI (by red boxes) as well as steps in which the cell changes its relations (by orange boxes).

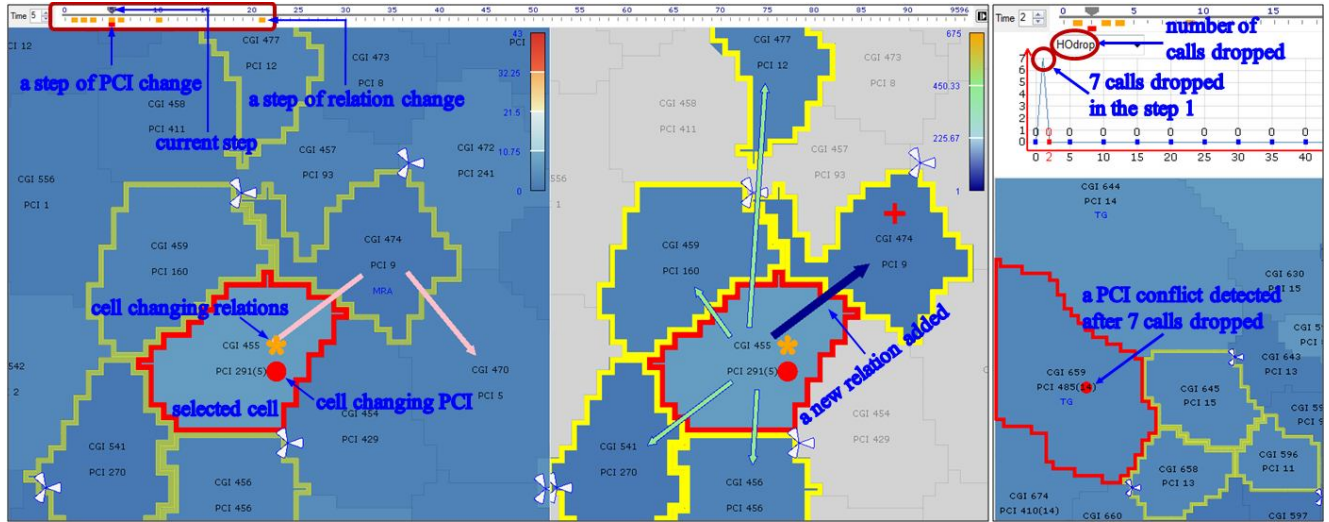


Figure 8. (left) an illustration of changes of a cell over time. Cell 455 changes its PCI in step 5 (marked by a red box) after a PCI conflict with cell 470 is detected, and changes its relations in steps 1, 2, 3, 5, 6, 10 and 21 (marked by orange boxes); (right) a PCI conflict detected between cell 659 and one of cells in its vicinity by method 'transmission gap' in step 2 after the cell has 7 call drops in step 1.

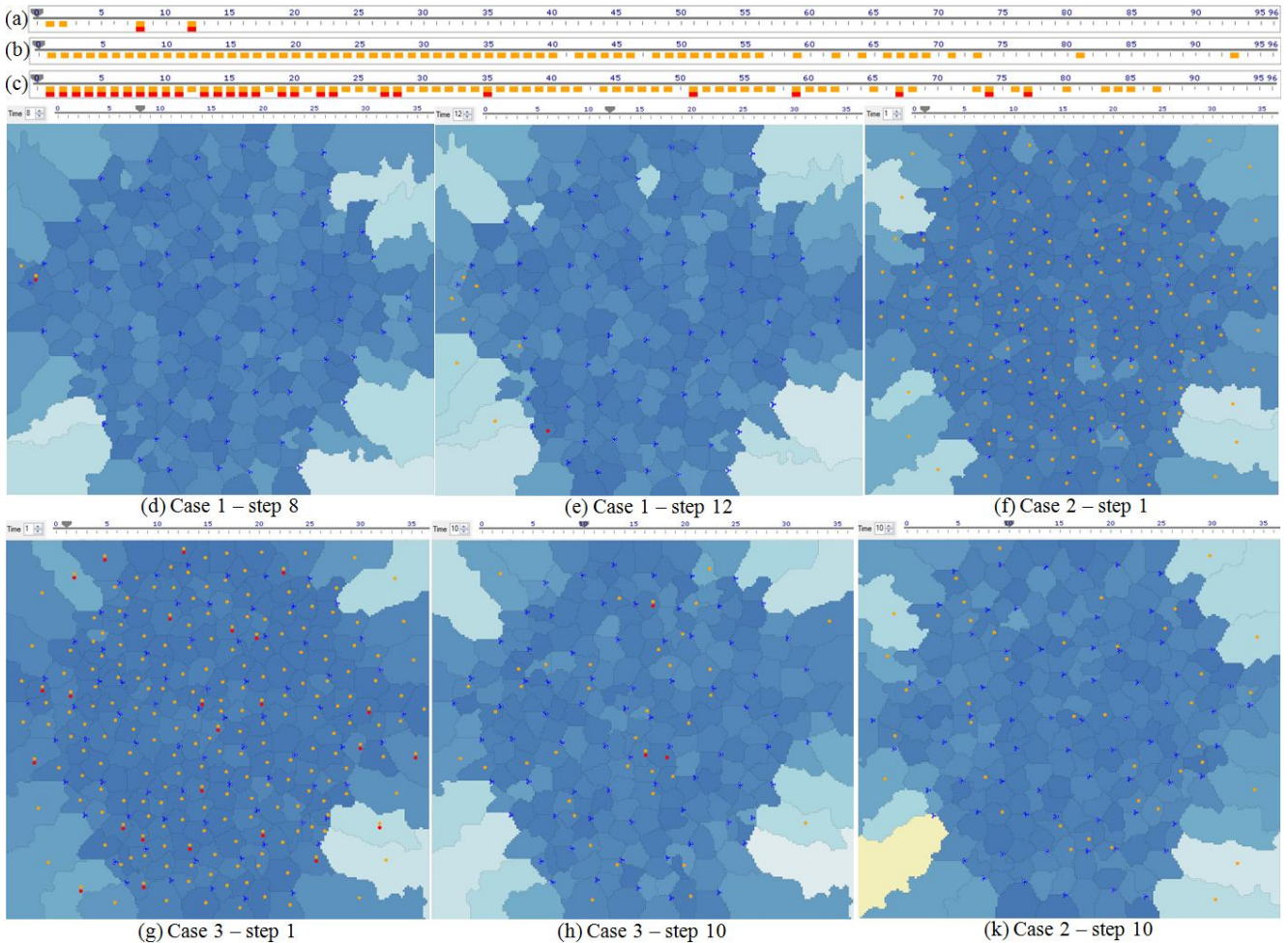


Figure 9. (a, b, c) Steps of change (PCI change and relation change) of the case 1, 2, 3 respectively; (d, e) cells of change of case 1 in steps 8 and 12; (f, k) cells of changes of case 2 in steps 1 and 10; (g, h) cells of changes of case 3 in steps 1 and 10.

Figure 9 illustrates how the network changes (or evolves) over time in the three experimental cases mentioned in the section III.B. In the case 1, there are few PCI conflicts detected and few relations added/removed. In case 2, there is no PCI conflicts detected. There are many relations added (or removed) in step 1, but there are fewer

relations added (or removed) in step 10. In case 3, there are many PCI conflicts detected and relations added (or removed) in step 10. All these facts make sense and agree with the initial configurations of the network in each case.

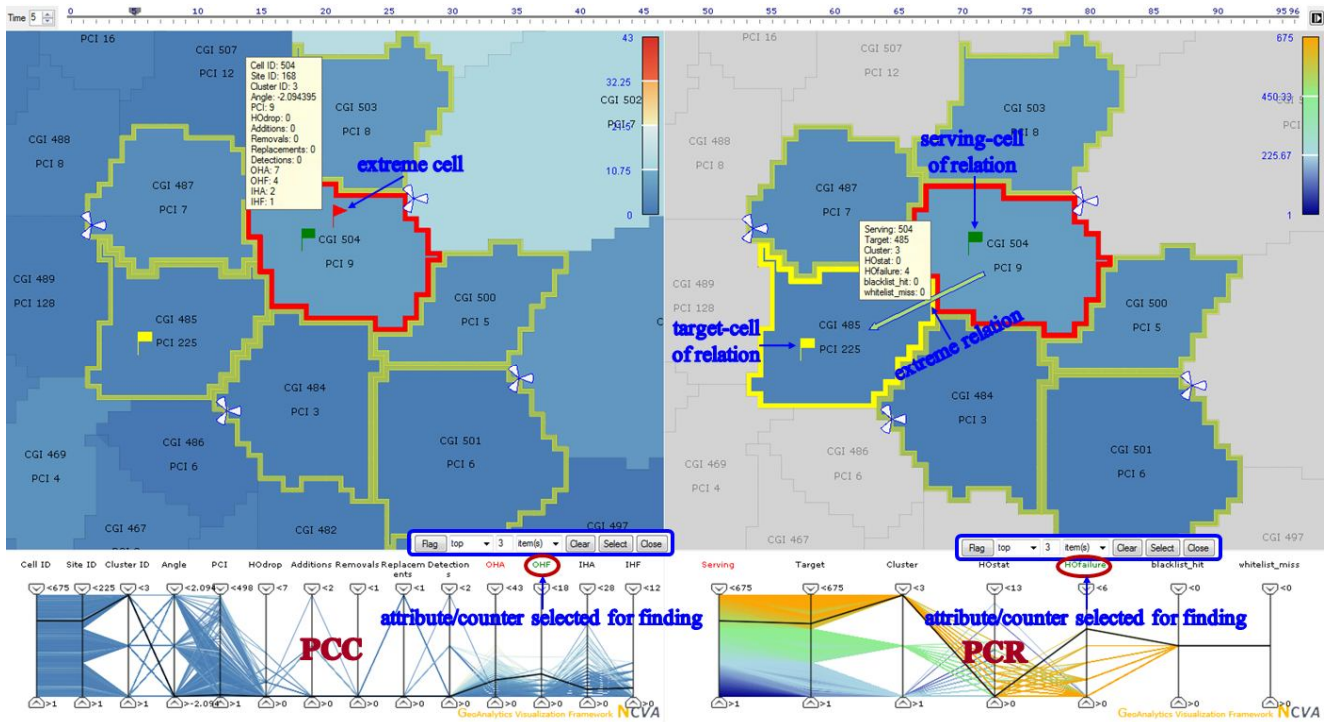


Figure 10. An illustration of finding extreme cells and cell relations. In step 5, cell 504 has four outgoing handover failures, and the relation from cell 504 to cell 485 also has four handover failures. This means the relation has a problem of handover failures.

G. Finding problems

There are various types of problems that can occur in the network and there are also many ways to detect them. One of these ways is to find extreme cells and relations that have extreme values for some attribute, for example, cells with large number of call drops or relations with large number of handover failures. The tool can do this by supplying the abilities to find cells and relations in the current time step that satisfied a specific condition and then mark them on the maps by special glyphs. The finding process can be performed through a graphical user interface (to specify the condition for finding) and the axes of the PCPs can be used to select the attribute/statistic for finding. Results from different finding processes then can be combined to increase the ability detecting problems. Figure 10 illustrates finding cells having large numbers of outgoing handover failures and cell relations having large number of handover failures in step 5. From finding results of finding we found that the relation from cell 504 to cell 485 has a problem of handover failed.

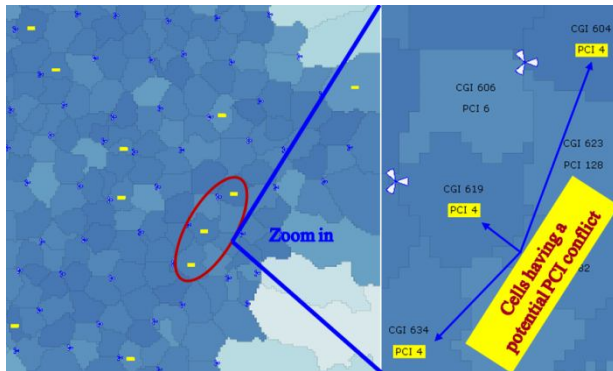


Figure 11. An illustration of cells with the same PCI in step 5. The cells 634, 619 and 604 have a potential PCI conflict.

Other type of problems is PCI conflicts. To be able to find potential PCI conflicts, a simple way is to highlight cell using the same PCI. Then cells that are in the vicinity of each other and use the same PCI would have a potential PCI conflict as illustrated in figure 11.

V. EVALUATION

A combination of domain experts from Ericsson and visual analytics researchers have been involved in the various stages of the prototype design and implementation, providing user feedback about usability and utility evaluation. The VoSON development followed a user-centric design approach [22]. The user-centric design process involved access to beta versions of the application, allowing focus group discussions. The overall involvement and reactions have been very positive from Ericsson. Many useful suggestions for improving the functionality were made and have been incorporated in successive implementation iterations. A number of characteristics of the current version of VoSON were derived from comments received during the evaluation phase.

The prototype has also been demonstrated for a few operators, and some preliminary indications can be noted. The concept of time line and the ability to see the network changing seems to attract the user “- I like the concept and the work with black and white lists and the view of changes over time, really good” and the ability to operate the network within the visualization tool seems also to be useful “- the handling of black and white lists looks very good to me”. On the negative side consistency and multi-vendor was mentioned, two important aspects not really related to visualization but usability. It can easily be seen that if the operator has a network from several vendors it is important that the cells in the map are the whole set and not a subset of his/her network; with a subset of cells the tool could be questioned.

Furthermore, we have seen that the inexperienced users start with the flagging feature rather than using filters to find the starting point for the search. If it is the amount of information in the PCPs or other complications that prevent them in the way we do not know for time being. But it seems that after a while “playing” with the controls and then suddenly they see new ways of finding interesting patterns – PCPs are accepted.

The tool now consists of a balanced subset of possible statistics and parameters from the radio network. For some users this will be enough; however, for other users there might be need for more information especially when to explain call drops not dependent on ANR. We now need to find out if and how that information shall be added.

VI. CONCLUSION AND FUTURE WORK

We have developed a visualization tool that visualizes a self-organizing network under the operation of ANR in collaboration with Ericsson. The tool is built based on the GAV framework. It combines interactive visual displays, a multi-layer approach and the ability to work with multi-dimensional, time-varying, geospatial and large scale data sets. It allows the operators to follow events happening in the network over time, supervise changes of the network over time and answer various types of questions such as why a relation is added or removed, why a cell changes its PCI, or how a PCI conflict is detected. These can help them to understand how the algorithm operates the network. The tool can also support the operators to examine various aspects of the network, find existing problems as well as potential problems. The tool was evaluated by a group of relevant domain users and the results from the evaluation were highly positive.

Our next step is to let users evaluate the tool with real massive data from real environment. We also expect to improve the performance and the interaction of the tool to support the operators better.

ACKNOWLEDGEMENTS

This applied research study was supported by Ericsson AB, Sweden. The research is also supported, in part, by funding from the Visualization Program managed by the Swedish Knowledge Foundation (KK-Stiftelsen).

We would like to acknowledge Thomas Rimhagen at Ericsson for ideas during the evaluation stage of the tool. Many thanks to our colleagues at the National Center for Visual Analytics NCVA (<http://ncva.itn.liu.se>) at ITN, Linköping University. Special thanks to everyone in the GAV development team.

REFERENCES

- [1] E. Dahlman, S. Parkvall, J. Sköld, and P. Beming, *3G Evolution: HSPA and LTE for Mobile Broadband*. Academic Press, 2007.
- [2] 3GPP TR 25.913, “Technical specification group radio access network; requirements for evolved UTRA (E-UTRA) and evolved UTRAN (E-UTRAN),” Release 7.
- [3] NGMN, “Operator use cases related to self organising networks,” ver. 1.53, 2007-04-16.
- [4] M. Amirijoo, P. Frenger, F. Gunnarsson, H. Kallin, J. Moe, and K. Zetterberg, “Neighbor cell relation list and physical cell identity self-organization in LTE”, in Proceedings of the 2008 IEEE International Conference on Communications Workshops, 2008, pp. 37-41.
- [5] D. Guo, M. Gahegan, A. M. MacEachren, and B. Zhou, “Multivariate analysis and geovisualization with an integrated geographic knowledge discovery approach,” *Cartography and Geographic Information Science*, vol. 32, no. 2, 2005, pp. 113-132, April 2005.
- [6] N. Andrienko, and G. Andrienko, “Interactive visual tools to explore spatio-temporal variation”, in Proceedings of the Working Conference on Advanced Visual Interfaces (AVI 2004), 2004, pp.417-420.
- [7] G. Andrienko and N. Andrienko, “Visual exploration of spatial distribution of temporal behaviors,” in *Proceedings of the 9th International Conference on Information Visualisation (IV05)*, 2005, pp. 799-806.
- [8] M. Jern, T. Åström, and S. Johansson, “GeoAnalytics tools applied to large geospatial datasets,” in *Proceedings of the 12th International Conference Information Visualisation (IV08)*, 2008, pp. 362-372.
- [9] D. A. Keim, C. Panse, M. Sips and S. C. North, “Visual data mining in large geospatial point sets”, in *IEEE Computer Graphics and Applications*, vol. 24, no. 5, pp. 36-44, September 2004.
- [10] W. Muller, and H. Schumann, “Visualization methods for time-dependent data,” in *Proceedings of the 2003 Winter Simulation Conference*, 2003, pp. 737-745.
- [11] J. C. Roberts, “Exploratory visualization with multiple linked views,” in *Exploring Geovisualization*, J. Dykes, A. M. MacEachren, and M.-J. Kraak, Ed. Oxford: Pergamon, 2005, pp. 159-180.
- [12] M. Jern, and J. Franzén, “GeoAnalytics – Exploring spatio-temporal and multivariate data,” in *Proceedings of the 10th International Conference on Information Visualisation (IV06)*, 2006, pp. 25-31.
- [13] M. Jern, S. Johansson, J. Johansson, and J. Franzén, “The GAV toolkit for multiple linked views,” in *Proceedings of the 5th International Conference on Coordinated and Multiple Views in Exploratory Visualization*, 2007, pp. 85-97.
- [14] S. Johansson, and M. Jern, “GeoAnalytics visual inquiry and filtering tools in parallel coordinates plots”, in *Proceedings of the 15th Annual ACM International Symposium on Advances in Geographic Information Systems*, 2007.
- [15] GeoVista Studio. [Online]. Available: <http://www.geovistastudio.psu.edu>.
- [16] D. Guo, J. Chen, A. M. MacEachren, and K. Liao, “A visualization system for space-time and multivariate patterns (VIS-STAMP),” in *IEEE Transactions on Visualization and Computer Graphics*, vol. 12, no. 6, pp. 1461-1474, November 2006.
- [17] M. Withall, I. Phillips, and D. Parish, “Network visualisation: a review,” *IET Communications*, vol. 1, no. 3, pp. 365-372, June 2007.
- [18] R. A. Becker, S. G. Eick, and A. R. Wilks, “Visualizing network data,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 1, no. 1, pp. 16-28, March 1995.
- [19] R. A. Becker, S. G. Eick, and A. R. Wilks, “Visualizing Network Data,” in *Readings in information visualization: Using vision to think*, S. K. Card, J. D. Mackinlay, and B. Shneiderman, San Francisco, CA: Morgan Kaufman, 1999, pp. 215-227.
- [20] E. E. Koutsofios, S. C. North, and D. A. Keim, “Visualizing large telecommunication data sets,” *IEEE Computer Graphics and Applications*, vol. 19, no. 3, pp. 16-19, May 1999.
- [21] E. E. Koutsofios, S. C. North, R. Truscott, and D. A. Keim, “Visualizing large-scale telecommunication networks and services,” in *Proceedings of IEEE Visualization '99*, 1999, pp. 457-461.
- [22] G. Andrienko, N. Andrienko, R. Fischer, V. Mues, and A. Schuck, “Reactions to geovisualization: an experience from a European project,” *International Journal of Geographical Information Science*, vol. 20, no. 10, pp. 1149–1171, November 2006.