Optimizing Dynamic Network Configurations

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INTRODUCTION

The Sámi Network Connectivity (SNC) project has a primary goal to provide Internet connectivity to The Sámi population in northern Scandinavia (Doria, 2004). They live as a nomadic people in sparsely populated wilderness areas where little connectivity is available. Since the area has a high level of protection from fixed installations and other man-made features, internet connection is proposed to be solved using a Delay Tolerant Network (DTN) with mobile routers. Research in for example probabilistic routing protocols and geographic modeling is preformed within the project.

In addition to the wilderness, the area is also characterized by reindeer herding and tourism (hiking) during the summer. Although the reindeer herding has very old traditions, the use of modern technologies are believed to be able to improve the herding operations substantially. Improved internet access has a clear potential for business development. In addition to that, there are also several social aspects to consider. Being connected in the wilderness area improves the conditions for combining old traditions with modern life.

The needs for network connectivity in this area may be illustrated by the following example. Apart from reindeer herding, tourism is an important source of income for the Sámi people. The Sámi camps usually have extra beds and cottages that can be used by the hikers. However, the availability of such beds and cottages are not known to the hikers. A web-based booking system that can be accessed with mobile terminals during the trip might be one part of a solution.

A DTN-based network (see figure 1) is here based on non-stationary routers, mobile relays and fixed gateways. The fixed gateways are installed at fixed locations, usually at the border of the wilderness area. These gateways have the usual access to the internet. The non-stationary routers can be placed at the Sámi camps or other strategic locations. Since they are located in the protected area, no fixed installations can be used. In addition, the Sámi people follow the movements of the reindeers. This means that some routers will move with the reindeers. The mobile relays finally, are small devices that are used as carriers of the information between the routers and the gateways. These relays can be placed in a backpack of a hiker, on a snowmobile, on a helicopter or any other moving object.

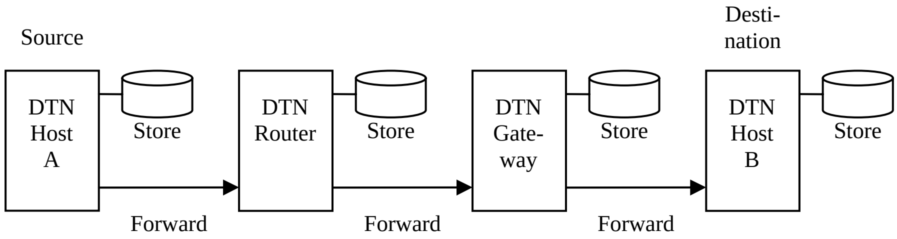

Figure 1. A DTN is a store and forward network, much like a postal system. DTN can unlike the Internet have intermittent connectivity, long or variable delay, asymmetric data rates and high error rates. In all nodes there is a potential delay and therefore storage is needed. The routers forward the message when possible (Cerf et al., 2005).

Placement of gateways and relays requires spatio-temporal modelling. Such a modelling includes dynamic allocation of gateways and routers, based on models of existing connectivity and traffic patterns.

The objective of this study is to find methods and to determine the proper placement of routing gateways and mobile routing relays. To solve this problem, theories from dynamic spatial modelling and economical analysis are used. The objective is also to find methods for calculating coverage maps, costs and expected delivery time dynamically depending on net configuration, travel movement statistics etc.

The study presented in this paper is limited to the Padjelanta summer villages. These villages are located along a trail and have been found suitable for the first tests. Another limitation is the selection of temporal periods, each one having its unique network configuration. Focus is here set on summer scenarios since it is easier to model movement when the main movement is along the trails.

GEOSPATIAL DATA PROCESSING

Spatiotemporal analysis

The concept of Map Algebra was introduced by Tomlin (1990). This concept has been further developed by for instance Takeyama and Couclelis (1997), where operations on multi-dimensional layers were introduced. Recently, Mennis et al. (2005) has extended the concept also into the spatio-temporal domain. A common characteristic of all these concepts are that the operations are based on thematic raster layers (or hypermaps or cubes).

Another approach to spatial analysis was made by Östman (2000), where the propagation of data uncertainties in data production was studied. This approach was not restricted to raster analysis and the notation also included vector data. In addition, operations on multi-dimensional data structures such as matrices and relations were defined. This paper will follow the approach by Östman (2000) but extended to the spatio-temporal domain, similar to Mennis et al. (2005).

A geospatial dataset ϕ is here considered to consist of a number of geospatial features. Each feature φ, is then represented by the triplet

$$\varphi = (x, t, a)$$
$$\varphi \in \phi$$

where x is a geometric element (point, line, polygon, pixel etc)
t is a temporal element (event, period)
a is a vector with other attributes

A temporal thematic map may then be defined as the mapping

$$TemporalThematicMap(x,t) = f(x,t,a_0)$$

where x is a geometric element (point, line, polygon, pixel etc)
t is a period in time
a_0 is a single-valued or multi-valued attribute

The type of operations that can be carried out depends on the domain of the temporal thematic map. If the domain consists of categorical values, operations such as reclassifications make sense. On the other hand, if the domain is ratio data, operations such as additions and multiplications may also be carried out. For multi-dimensional data such as matrices, matrix operations such as addition, multiplication, inverse etc can be defined.

In general, operations on temporal thematic maps can be written as

$$OutputLayer(x,t) = Operation(InputLayer_1(y,s), InputLayer_2(y,s),..., InputLayer_n(y,s))$$
$$\forall y : Condition(y,s,x,t) = True$$

Tomlin (1990) classified the operations into different classes, depending on which geometric elements (pixels in Tomlin's case) that were involved in the operation. Table 1 shows the Tomlin operations and its relation to the conditions being applied. Tomlin also defined incremental functions, which here are considered as geometric operations on adjacent elements (focal functions on geometric properties).

Type of operation	Spatio-temporal condition
Local functions	$y = x, s = t$
Focal functions	$(y,s) \in Neighborhood(x,t)$
Zonal functions	$Zone(y,s) = Zone(x,t)$

Table 1. Conditions for operations on temporal thematic maps

Decisions to optimise cost-benefit

Rational decisions may be defined as decisions aiming to optimise a certain utility function. Often, such utility functions are defined using cost and benefit functions. In many cases, these functions have different units of measure. If that is the case, some kind of weighting has to be done.

Assume that the costs and benefits can be estimated through spatio-temporal analysis and that the net benefits can be estimated through some kind of weighting. For a given period of time (t_i), the net benefit may then be estimated as

$$NetBenefit(x,t_i) = f(Costs(x,t_i), Benefits(x,t_i))$$

An investment is often characterised by an initial cost while the benefits arises in future periods of time. The value of an investment may then as a consequence be defined as the future expected net benefits, or

$$Value(x,t_i) = \sum_{j=i}^{\infty} NetBenefit(x,t_j)$$

As usual, the net benefits should be adjusted by a suitable depreciation factor. In addition, the spatial distribution of the net benefits might not always be of interest. In such cases, global aggregates may be used.

The future net benefits are however often affected by the decisions we make and other expected (and unexpected) future events (Bateman, 2003). In addition, as Nash et al. (2003) points out, multivariate optimization is usually preferred. If then the number of possible solutions is large, genetic algorithms can be used to solve the optimization problem (Nash et al., 2003).

Estimation of benefits

In this study, costs and benefits are used for optimising the dynamic network. The costs are related to the network configuration while the benefits are related to the number of users being connected and the performance of the network. Other measures of benefits, for instance income expressed in monetary terms, may of course be used. In this study, a detailed business model has not yet been developed. As a consequence, the number of users is used as a measure of benefits.

For a given period of time, the benefits of the network depend on the current network configuration and the spatial distribution of the users. The network configuration is the decision which we try to optimize. The spatial distribution of the users on the other hand is dependent on a variety of factors, for instance the distribution of reindeers. But since their movements have a strong random component, probabilistic distribution maps have to be used. A set of probabilistic maps are here, for a given time period j, defined as

$$SetOfProbabilisticMaps = \{(p_i, ProbabilisticThematicMap_i(x,t_j))\}$$

$$\sum_{i=1}^{n} p_i = 1$$

Where p_i is the probability of thematic map i

Based on knowledge about reindeer movements and the corresponding movement of Samí people, a set of probabilistic population maps has been created. The population is assumed to be distributed around cottages, along paths, within Sámi villages or in the area of calf marking. Depending on the period of time, the densities vary. Then, for each time period, an expected population map (see figure 2) is estimated as the weighted mean map.

$$ExpectedPopulationMap(x,t_j) = \sum_{i=1}^{n} p_i \cdot ProbabalisticPopulationMap_i(x,t_j)$$

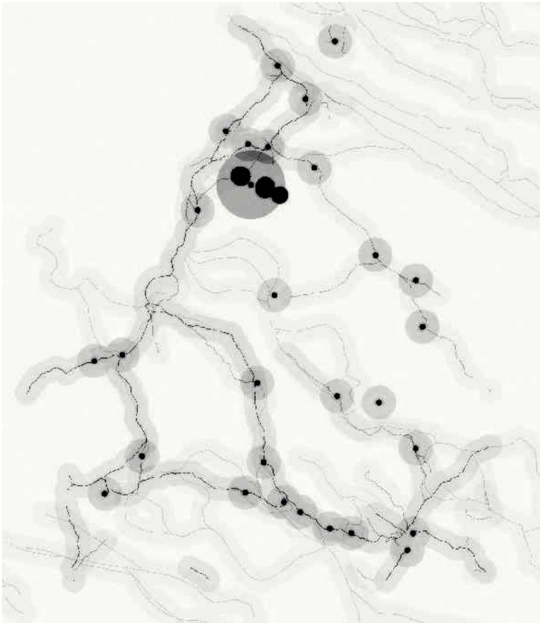

Figure 2: Expected population density during period t_1 (the marking of calves). Population density is shown with population ranging from light to dark where dark represents a larger number of people. People are believed to reside along the paths and around the cottages. The darkest area in the middle represents the area for marking of calves.

Based on the probabilistic population maps, a number of different network configurations have been created, using traditional space allocation procedures. Figure 3 shows an example of such an analysis. The differences in network configurations depend on the locations of non-stationary routers and on the number of mobile relays.

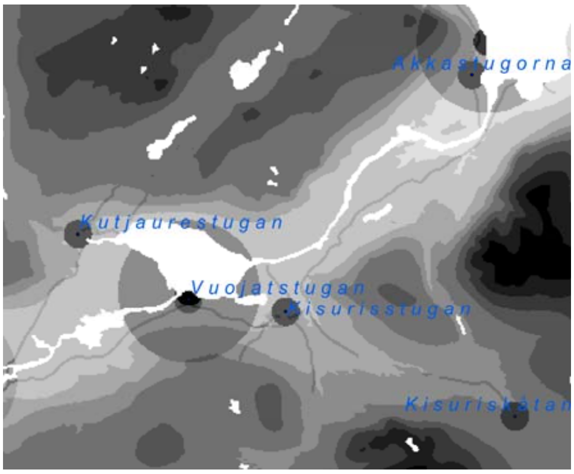

Figure 3: Dark areas shows places that are suitable for placing routers when combining data from elevation, vegetation, cottages, population and paths. White areas are unsuitable (for example lakes).

For each network configuration being defined, a coverage map was created using traditional viewshed analysis (figure 4). It would be more correct to use software for radiowave propagation, but due to the limited quality of the source data, a simple viewshed analysis was found to be sufficient.

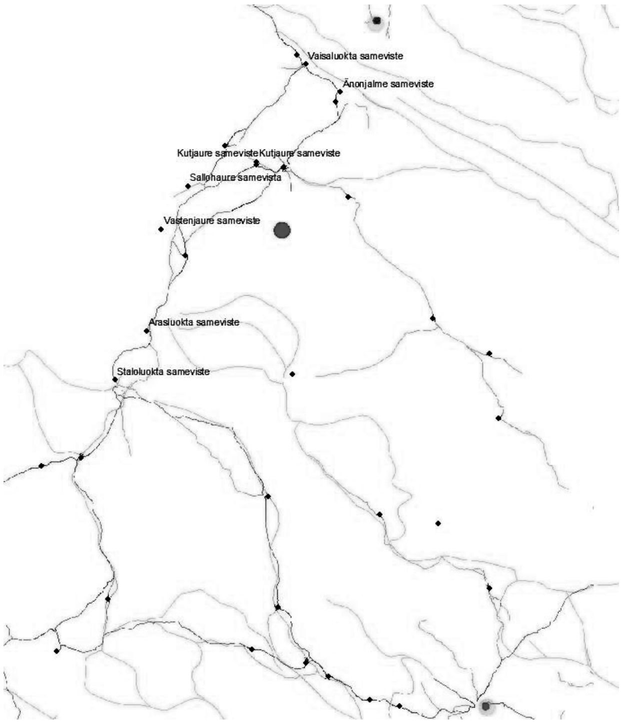

Figure 4: Coverage for one DTN configuration, during the marking of calves period, t_1.

By overlaying the expected population map with each coverage map, the expected number of users for each configuration j can be estimated as

$$ExpectedNumberOfUsers_j(x,t) = DTNCoverage_j(x,t) \cdot ExpectedPopulationMap(x,t)$$

where *DTNCoverage* is a binary spatiotemporal map showing the coverage of the network

ExpectedPopulationMap shows the expected number of persons

Estimation of costs

For a given period of time, the cost for network configuration depends on the current configuration, movement costs from the previous configuration and costs per network item in each configuration.

$$Cost_j(x,t) = f_1(DTNConfiguration_j(x,t), DTNConfiguration_k(x,t-1), ItemCost)$$

The item costs are costs for acquiring and maintaining each piece of equipment. These costs also include expected loss of equipment. It this specific study, the equipment being used was prototypes, not commercial products. As a result, the equipment costs being used reflect the assumed costs on a future market. It was also assumed that the equipment was bought, not based on leasing contracts or similar. It should be stressed that if leasing contracts are used, the temporal dimension of the cost model is even more important, since such contracts allows for a larger variability of equipment over time.

RESULTS

In this study, three time periods was used for the summer period, namely before, during and after the marking of calves ($t_0 – t_2$). For each time period, three possible network configurations have been designed. Each network configuration consists of the following interacting types of network components

- Fixed gateways, placed in Kvikkjokk and Ritsem
- Non-stationary routers, placed in Sámi villages and path crossings
- Mobile relays, placed in helicopters and handed out to foot hikers

Since the costs and benefits are not measured in the same units (monetary costs and number of users), two-dimensional analysis has to be made. The visualisation for such analysis depends on the policies for optimizing the cost and benefits. In this study, it is assumed that this type of network has to be supported by some kind of societal fund. One optimizing model may then be based on the decision that the network shall always cover at least a certain number of users see figure 5.

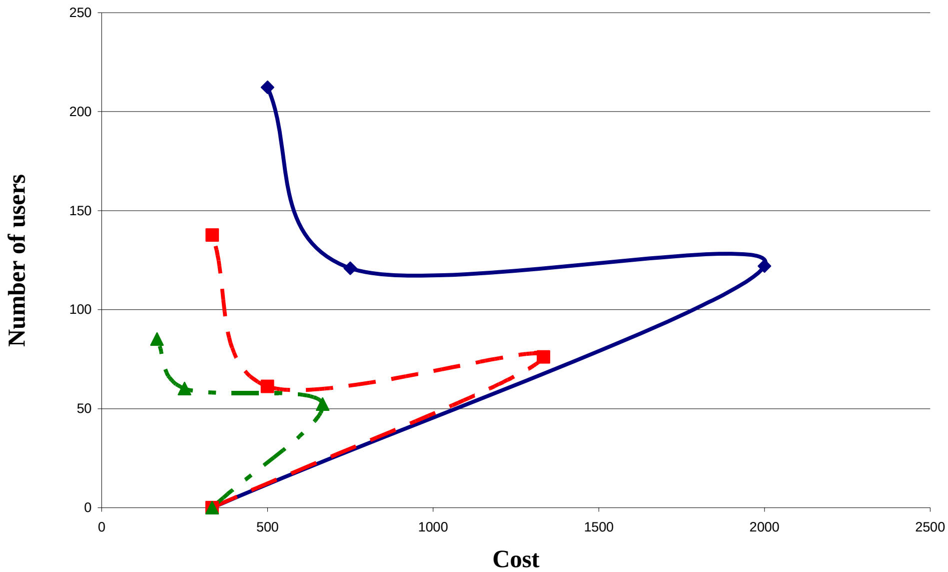

Figure 5: Costs and Benefits for three series of DTN Configurations, 1-4-7 (dotted-dashed), 2-5-8 (dashed) and 3-6-9 (solid). Each vertex on the line corresponds to a time period. The first vertex is the current period of time (decision point) and it is common to all alternative series of configurations.

Assume that we require at least 100 persons to be covered by the DTN network. For simpler visualisation, figure 5 shows only three out of 27 possible configuration series. Of these three series, only series 3-6-9 fulfil the demand of always covering at least 100 persons. Other possible combinations are not shown in figure 5, but due to the design of the current cost model, other combinations show similar patterns.

DISCUSSION AND CONCLUSIONS

In this study, methods for spatio-temporal analysis have been developed. The approach based on spatio-temporal map algebra has shown to be successful. However, the only temporal elements that have been used are time periods. Events (points in time) and operations (continuously changes in time) have not been used. Further exploration of these types of elements is encouraged.

The estimates of benefits are hampered by the lack of reliable data. Information about the Sámi population as well as tourists (number and movements) has been obtained through interviews and discussions. More reliable data of the Sámi movements may for instance be acquired by GPS logging. The usability of more reliable data can be studied using Monte-Carlo simulation techniques, but at the time being, it is still too early for such analysis.

The estimates of the costs are hampered by the lack of reliable pricing mechanisms. Some parts of the equipment are only available as prototypes and its commercial conditions are not yet known. This applies both to prices as well as conditions for procurement and leasing. In addition, the policies for balancing cost and benefits are not decided. It should also be noted that such policies will be a matter of negotiations also in the future. However, the uncertainty on the financial terms and conditions implies that the current need for more detailed information about population and tourist movements is fairly limited.

The visualisation of multivariate optimization is to a large degree depending on the overall decision making process and the corresponding utility functions and business models. Even in two-dimensional optimization, the visualisation is far from trivial.

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