A Sustainable Connectivity Model of the Internet Access Technologies in Rural and Low-Income Areas

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Abstract. The Internet has evolved as a critical booster for the economic, social and technical development of human society. Almost half of the world's population is unfortunately missing out due to the lack of access to the Internet. Such users are mainly those living in rural and low-income areas. Various strategies and approaches for improving the Internet's accessibility are available, each with a different set of benefits, costs, and risks. It is important to choose solutions from these feasible options that promise to promote the efficiency as well as the sustainability of the 'Internet Ecosystem'. In this paper, we propose a new model of *sustainable connectivity* that integrates three factors (affordability, social shareability, and geographical network coverage) that must be considered in the selection and design of Internet access solutions. In addition, we develop a hypergraph-based network graph solution that illustrates the relationship among the three factors. Then, we use Coloured Petri Nets (CPNs) to model and simulate the possible Internet access solutions and also interplay those three factors to study how they impact the overall network connectivity performance. Our initial results have revealed how sustainable Internet connectivity behaves as a function of the affordability, social interaction, and geographical network coverage and investigates how these factors could be leveraged to provide different network connectivity and Internet access solutions.

Keywords: Internet access · Sustainable connectivity
Rural and low-income areas · Affordability · Social shareability
Geographical network coverage · Hypergraph theory · Coloured Petri Nets

P. H. J. Chong et al. (Eds.): SmartGIFT 2018, LNICST 245, pp. 93–102, 2018.
https://doi.org/10.1007/978-3-319-94965-9_10

1 Introduction

The Internet is vital for a nation's development and its social and economic growth. An open, secure, trustworthy, and universally accessible Internet can facilitate greatly in attaining the United Nations defined Sustainable Development Goals (SDGs) [1]. The 17 goals include ending poverty, protecting the planet, and guaranteeing prosperity to all humankind. Although Internet penetration rates are high (over 80%) in developed countries [2], the people living in rural and low-income areas generally face access problems with limited or non-existent connectivity (60% of offline population live in rural areas [3]). Internet connectivity in these areas is challenging because of barriers such as remoteness of hard-to-reach rural areas, low density of users, and low-income of users.

Internet access in New Zealand is facing similar challenges [4], and the New Zealand Government has launched several initiatives to extend Internet connectivity in rural areas [4]. One of them is the Rural Broadband Initiative (RBI), a partnership among the Government and different providers to deploy broadband solutions in rural areas. Despite RBI's progress, rural users are still demanding higher and higher data rates, and more reliable and affordable Internet access. According to the participants in the Rural Connectivity Symposium [5], there is an urgent need to deploy Internet services and networks in order to support health services, such as emergency healthcare services, and to have different connectivity options given that there will be no one-size-fits-all solution. The discussions in the symposium also highlighted the priorities for improving rural connectivity, which include the identification of opportunities for boosting rural economic activity and productivity levels.

Harrison *et al.* [6] have defined the factors which have some impact in the deployment of connectivity infrastructure initiatives and projects, such as: the availability and quality of the Information and Communication Technology (ICT) infrastructure, the accessibility to the Internet for education, communication and health services, and affordability as some of the digital divide indicators [7]. These factors still hold in rural cases.

In this paper, we propose a sustainable connectivity model for rural and low-income areas, in order to provide Internet access. The model is based on the following pillars: affordability, social shareability and geographical network coverage. Based on these pillars, we then analyse the reachability of users to identify network access technologies suitable for the rural and remote users. More formally, the reachability of users for each individual factor can be represented as a graph. We then use a hypergraph to model the relationship between the different features, where each dimension of the hypergraph refers to one reachability area. In this way, we are able to leverage on the hypergraph theory [8, 9] to identify the optimal access technologies. Moreover, we use Coloured Petri Nets (CPNs) [10] to demonstrate the applicability of our proposed model. In particular, the outcome is a set of results showing the percentage of suitable connections for several optimistic and pessimistic assumptions. Employing CPNs to simulate different scenarios has the advantage of offering initial insights into the model effectiveness at a high level of abstraction, while still being able to include detailed scenario models and to obtain more realistic results in the future.

The paper is organized as follows. Section 2 provides an overview of the affordability, social and geographical critical factors with special emphasis in the New Zealand context. Section 3 then presents a sustainable connectivity model for Internet access in rural and low-income areas. Section 4 then reports the results, which are obtained by applying CPNs on the considered case study. Finally, Sect. 5 concludes the paper.

2 Related Work

In this section we review the literature by identifying the importance of considering the reachability of users based on these factors.

Social shareability represents the willingness of users to share their network connections so other users can gain access to the Internet through the shared connection. The idea of sharing the Internet connection for social purposes has already been proposed as a solution for providing connectivity to low-income families living in an urban area in [11]. Vural *et al.* [12] identified the sharing of broadband connections as one of the attractive options for increasing wireless connectivity in urban areas when deploying wireless mesh networks.

Focusing on the affordability, the UK telecommunications regulator defines this aspect as the capability of a good or service to be purchased by a consumer without suffering undue hardship [13]. Affordability is one of the digital divide factors, meaning that some rural users may not be able to afford Internet access [7]. In this context, the reachability of the affordability means that a user can pay for the connection given the Internet access cost. In particular, the authors in [14] introduce a reachability analysis given the wages of the users.

In [4], several potential approaches for providing broadband connectivity in rural areas of New Zealand are discussed. The authors consider the socio-technical needs of the potential rural users in order to get them engaged in the development of their connectivity solutions. Moreover, a set of four rural access technologies is overviewed. In this context, "geographical reachability" means that a user can reach another user to establish a communication link. The abovementioned technologies provide different network coverage and support different levels of user mobility which need to be taken into account for a geographical reachability analysis. Moreover, Durairajan *et al.* [15] propose a framework for identifying opportunities for broadband connectivity deployment. The authors consider different factors, including: the infrastructure availability, the user demographics, and the deployment costs. Differently from our work, the complex relationships among the defined factors are not considered. Moreover, both social and affordability factors are not taken into account.

In our work, we adopt hypergraph theory and CPNs. Hypergraph theory is a powerful tool to model complex relationships among objects within a system. For example, Bai *et al.* [16] propose a hypergraph framework to formulate the complex relationships among the entities in a caching based D2D communication system. Hypergraphs are beneficial for our research as they allow reachability analysis across multiple dimensions (factors) and can be used to find optimal solutions with respect to the selected Internet access technology. Moreover, CPNs have been used extensively to build models of distributed systems at different levels of abstractions, and to obtain numerical simulations results [10]. They are beneficial for our research because we can abstract away from many details and we can easily obtain a set of initial results.

3 A Sustainable Connectivity Model for Rural Zones

The proposed sustainable connectivity model includes three factors: affordability, social shareability and geographical reachability as shown in Fig. 1. It also shows the possible relationships among these three factors associated with the potential access technologies, thus we can evaluate these technologies through a 3D-perspective. Here we denote the x-axis as the geographical reachability, the y-axis as the affordability reachability and the z-axis as the social shareability. For example, the D2D wireless communications technology with mesh networking could be a suitable access solution when the social shareability is high, but the geographical reachability is low. In order to measure the possible technological solutions for selection, we could use this sustainable connectivity model to leverage and to optimize the cooperation among the three variables while keeping fixed the total amount of the resources.

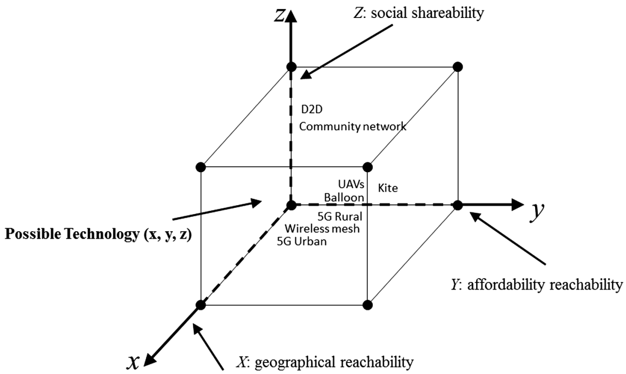

Fig. 1. The three-dimension based sustainable connectivity model.

Figure 1 does not fully capture the model, as the shareability and reachability factors are not singular values but rather complex relationships between users in a particular area. Therefore, the initial sustainable connectivity model needs to be further enhanced by representing it as multiple graphs with different layers. Figure 2 reports a representative example of a 13-node network. In the geographical dimension, the nodes represent the user locations, and the links represent the existing physical connections, e.g., cables or fibres already established between two users by the infrastructure provider. In the affordability dimension, the links between two nodes represent the fact that one user can afford to connect with another. Finally, in the social dimension, each link represents the two users with willingness to allow sharing their devices to connect with each other wirelessly so as to extend the Internet connectivity.

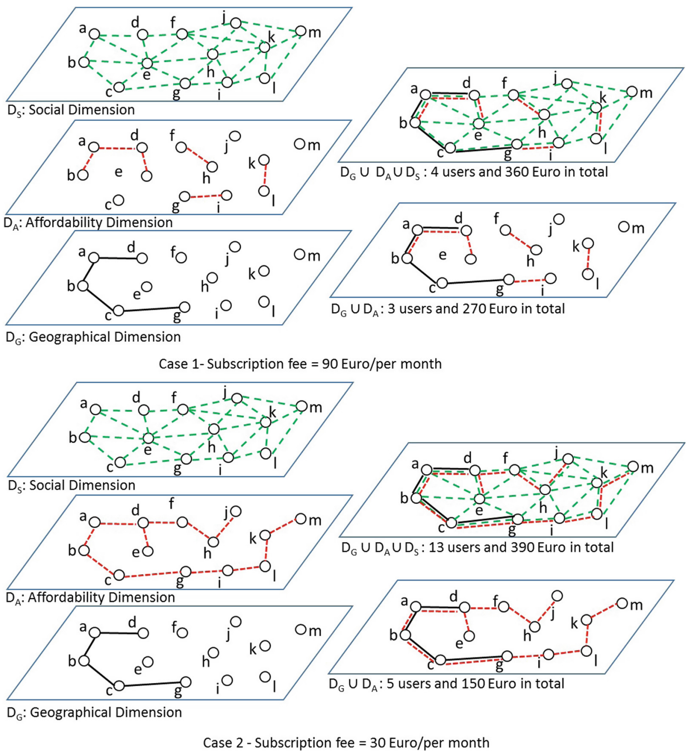

Fig. 2. An example of sustainable connectivity model exploiting multi-dimensional graphs.

We then further consider two representative cases (reported in Fig. 2). In the first one (top part of Fig. 2), we assume that the subscription fee to the Internet service is very high, i.e. 90 [EUR] per month. Firstly, we consider both geographical and affordability factors i.e., $D_G \cup D_A$, for the Internet access. It can be seen that only three users (i.e., *a*, *b* and *d*) can access the Internet while users *c* and *g* have network connectivity but they cannot afford it. On the other hand, users (*f*, *h*, *g*, *i*, *k*, *l*) can afford it but they do not have network connectivity yet so they cannot access the Internet either. In rural areas, neighbourhoods in small towns or villages usually tend to cluster people in relatively small areas. Therefore, we can assume denser link connectivity in its social dimension. In other words, the users have willingness to support and share their Internet connectivity to each other if the network security and payment issues can be addressed. In this case, the social shareability factor can be included (i.e., $D_G \cup D_A \cup D_S$) and D2D mesh networking can be set up among users; in this scenario, there is an extra user who can be further connected to access the Internet service.

Focusing on the second case (bottom part of Fig. 2), we reduce the monthly subscription fee from 90 Euro to 30 Euro. As a result, more users can afford it, i.e., more links in the affordability layer are established, while the links in the other two dimensions are kept unchanged. It can be seen that there will be 5 users who can access the Internet when both geographical and affordability factors are considered. This number is increased to 13 users when all three factors are considered. From the network operator's perspective, the option of having more users (i.e., 5 users vs. 3 users) but with lower profit (i.e., 150 Euro vs. 270 Euro) is not a feasible solution. On the other hand, the solution of having more users (i.e., 13 users vs. 3 users) with more profit (i.e., 390 Euro vs. 270 Euro) could be an attractive option to pursue. This could be a win-win solution between the network operators and end-users.

As shown above, the traditional graph approach is not sufficient to holistically model the complex relationships between affordability, geographical reachability and social shareability. In order to explore the interplay among these three factors, we can represent our sustainable connectivity model by using multi-dimensional graphs through the use of hypergraph theory. Hypergraph theory provides the mathematical foundation required to formulate the complicated relationship among these factors. It can also facilitate the understanding of those relationships and allow us to carry out further studies of our proposed model. The hypergraphs are extensions of graphs which can model more general types of relationships [9]. The formal definition of a hypergraph is as follows.

Definition 1. A Hypergraph is a pair $H = (V, E)$, where

1. $V = \{v_1, v_2, v_3, \ldots, v_n\}$ is the set of vertices or nodes
2. $E = \{E_1, E_2, \ldots, E_m\}$, E_i is a subset V, for $i = 1, \ldots, m$, is the set of hyperedges.

If the hypergraph does not have any isolated vertex

$$\bigcup_{i}^{m} e_i = V$$

An isolated vertex x is defined as

$$x \in V \setminus \bigcup_{i}^{m} e_i$$

A hyperedge e is a loop if $e \in \mathrm{E}$ such that $|e| = 1$

In order to study the relationships among the three factors, we propose a hypergraph representation of the sustainable connectivity measurement model. We denote the set of the communication network users as V^c, where x_n^c is the nth user of the communication access network. The set of users which may have a social interaction is denoted by V^s, where x_m^s is the mth user. We denote the set users in the affordability graph as V^a. The set of vertices in the proposed hypergraph is defined as:

$$V^c \cup V^s \cup V^a = V$$

In the considered hypergraph for the sustainable connectivity measurement model, a hyperedge exists if and only if:

- Two users of the given communication network, which belong to V^c, are willing to establish a communication link.

- One of them is interested in sharing the connection with the other user x_m^s.
- One of the users, x_n^a can afford the connection.

The benefit of representing the three factors as a hypergraph is that efficient analysis techniques can then be used to identify optimal solutions. As shown in the examples of Fig. 2, for a target area for deploying Internet access, it is possible to generate hypergraphs for different access technologies, given the users and the geographical data (e.g. income data, social interactions such as phone call frequencies, mobility patterns, and radio signal propagation maps). The analysis of the hypergraphs could reveal which access technologies can provide suitable Internet access to the most users with the least cost.

4 A Case Study Based on Coloured Petri Nets

Having considered the sustainable connectivity model as a hypergraph, we want to better investigate the potential of the proposed three-dimensional solution. In this context, we adopt CPNs as a modelling and simulation tool because they allow the creation of models at different levels of abstraction. Thus, we can generate models that represent the three dimensions of the sustainable factors at a level of abstraction. This model captures the functional properties which need to be proved and allows us to analyse the system despite its intrinsic complexity.

In the following, we describe how the CPNs are exploited. In particular, we exploit the hierarchical constructs of CPNs [10]. The top-level module is shown in Fig. 3, which depicts a three-dimensional representation of the model shown in Fig. 2. This module includes a *substitution transition* (drawn as rectangles) for each reachability dimension, each of them defined by its own module. In the figure, the *place* (drawn as ellipses) named "*Users*" represents the users of the communication access network who may want to interact with other users and may be able to afford the connection. The place named "*SysState*" represents the state of each sub-system, i.e., affordability, social shareability and geographical reachability. Places and transitions are connected by *arcs* which have expressions associated with them.

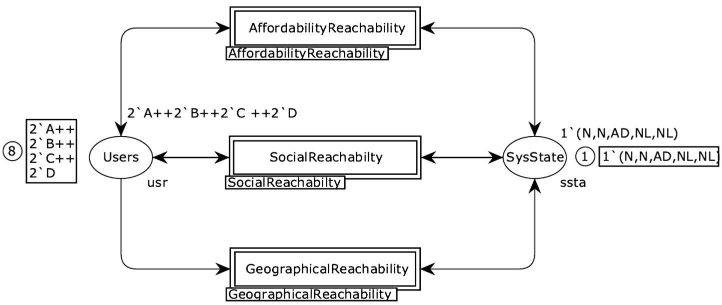

Fig. 3. Top view of the CPN module for the sustainable connectivity model.

We conduct simulations for the scenarios shown in Table 1. Each scenario is defined by three probability variables in the simulation: the probability of affordable reachability (p_a) means that the user can afford a connection with probability p_a; the probability of social shareability (p_s) means that a user has a chance to share the connection with another user with probability p_s; and the probability of geographical reachability (p_g) means that the user can reach another user with probability p_g. The probability values have been chosen to represent either pessimistic scenarios (i.e. scenarios 4, 5, 6, and 8) or optimistic ones (i.e. scenarios 1, 2, 3 and 7). Examples of the scenarios are shown in Fig. 2 and described in Sect. 3.

Table 1. Simulation scenarios

Scenario	Description	Affordability	Social	Geographical
1	Poor geographical reachability	0.9	0.9	0.3
2	Poor social links	0.9	0.3	0.9
3	Poor affordability	0.3	0.9	0.9
4	Poor geographical reach. & social	0.9	0.3	0.3
5	Poor geographical reach. & afford.	0.3	0.9	0.3
6	Poor afford. & social links	0.3	0.3	0.9
7	Optimistic	0.9	0.9	0.9
8	Pessimistic	0.3	0.3	0.3

Figure 4 shows the module for the reachability of an affordable connection (the social shareability and the geographical reachability modules are similar). For the sake of simplicity, we use a uniform distribution to represent the probability that a user can afford a connection. We conduct simulations for a network with four nodes (A, B, C and D), which is shown in Fig. 3. The initial marking (i.e. the initial state of the system) is the initial distribution of tokens to the model places, where a *token* is a value (colour), which belongs to the type of the place.

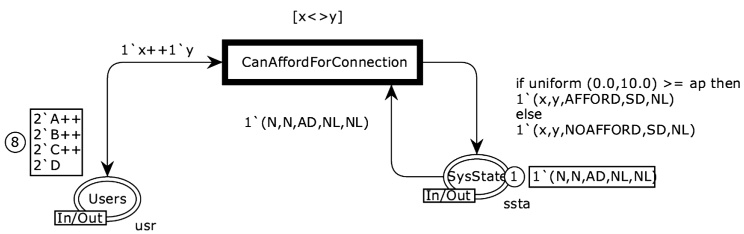

Fig. 4. Reachability module for the affordability factor.

Figure 5 reports the simulation results in terms of the reachability states for scenarios 1–8. A reachability state shows the state of each graph of the system where *Can Afford* means that a user can afford the connection, *Social Shareability* means that the user can (or is willing to) share the connection, and *Network Coverage* means that the user is in the geographical area of the network. The reachability state 4 is the desired state where two users who are interested to share the connection with each other can establish a communication link and pay for the Internet access service (i.e., a hyperedge exists). In the scenarios where two or more of the reachability factors are favourable (i.e., scenarios 1, 2, 3 and 7), we can see that there is a better chance to reach the desired reachability state. On the other hand, if at least two reachability factors are poor, there is a low chance to get the users interacting by exploiting an affordable physical connection. Moreover, the percentage of users who cannot interact because of at least one factor is not met is at most equal to 20% or lower in most of the scenarios.

1	Can't Afford	Social Shareability	Network Coverage	5	Can Afford	No Social Shareability	No Network Coverage
2	Can Afford	Social Shareability	No Network Coverage	6	Can't Afford	No Social Shareability	Network Coverage
3	Can Afford	No Social Shareability	Network Coverage	7	Can't Afford	Social Shareability	No Network Coverage
4	Can Afford	Social Shareability	Network Coverage	8	Can't Afford	No Social Shareability	No Network Coverage

Fig. 5. Percentage of connections for each reachability state

5 Conclusions and Future Work

In this paper we have proposed a sustainable connectivity model of the Internet access in rural and low-income areas. Our model takes into account affordability, social shareability and network geographical coverage factors. We represent our solution as a three-dimensional graph by using hypergraph theory. We then use CPNs to model the 3D graphs and to represent the considered factors at different level of abstractions. By exploiting our model, we have provided insights into more detailed information of users such as whether a user likes to share the connection with others or not, with existing physical connectivity or not, as well as whether they can afford the intended connection or not. All of this information is helpful to evaluate different access technologies. We have then conducted a simple, yet representative, simulation study, by taking into account both optimistic and pessimistic scenarios. Our preliminary results confirm the effectiveness and the potential of our model.

As future work, we plan to provide more complex sustainable connectivity models to accurately capture the affordability, social and geographical situations and their dynamics in the rural areas. Moreover, we will perform a tech-economic analysis for comparing various access technologies in real rural and low-income areas to validate the credibility and the scalability of our model.

References

1. United Nations: Sustainable Development Goals: 17 Golas to Transform our World. http://www.un.org/sustainabledevelopment/sustainable-development-goals/#. Accessed 03 Jan 2018
2. Internet World Penetration Rates. http://www.internetworldstats.com/stats.htm. Accessed 15 Dec 2017
3. Philbeck, I.: Connecting the Unconnected: Working Together to Achieve Connect 2020 Agenda Targets (2017)
4. Villapol, M., et al.: Connecting the unconnected 10% of New Zealanders by 2025 : is a MahiTahi approach possible? In: Proceedings of 27th International Telecommunication Networks and Applications Conference, ITNAC, Second International Workshop on Data Intensive Computing and Communications for Sustainable Development (2017)
5. Connecting Rural New Zealand-Insights from the 2017 Rural Connectivity Symposium (2017)
6. Harrison, C., et al.: Foundations for smarter cities. IBM J. Res. Dev. **54**(4), 1–16 (2010)
7. Barzilai-Nahon, K.: Gaps and bits: conceptualizing measurements for digital divide/s. Inf. Soc. **22**(5), 269–278 (2006)
8. Berge, C.: Hypergraphs: Combinatorics of Finite Sets, vol. 45. Elsevier, Amsterdam (1984)
9. Bretto, A.: Hypergraph Theory: An Introduction, vol. 53. Springer, Heidelberg (2013). https://doi.org/10.1007/978-3-319-00080-0
10. Jensen, K., Kristensen, L.M.: Coloured Petri Nets. Springer, Heidelberg (2009). https://doi.org/10.1007/b95112
11. Villapol, M.E., Abreu, D.P., Cordero, C.: Planning a wireless mesh network which takes advantage of the Urban geography of the city. In: Proceedings - 2015 Asia-Pacific Conference on Computer-Aided System Engineering, APCASE 2015 (2015)
12. Vural, S., Wei, D., Moessner, K.: Survey of experimental evaluation studies for wireless mesh network deployments in Urban areas towards ubiquitous Internet. IEEE Commun. Surv. Tutor. **15**, 223–239 (2013)
13. Ofcom: Results of research into consumer views on the importance of communications services and their affordability (2014)
14. Barrantes, R., Galperin, H.: Can the poor afford mobile telephony? Evidence from Latin America. Telecommun. Policy **32**(8), 521–530 (2008)
15. Durairajan, R., Barford, P.: A techno-economic approach for broadband deployment in underserved areas. ACM SIGCOMM Comput. Commun. Rev. **47**(2), 13–18 (2017)
16. Bai, B., Wang, L., Han, Z., Chen, W., Svensson, T.: Caching based socially-aware D2D communications in wireless content delivery networks: a hypergraph framework. IEEE Wirel. Commun. **23**(4), 74–81 (2016)