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A decision support scheme for solving the mobile coverage gap in rural areas in developing countries – Demonstrated with a case in Indonesia

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ABSTRACT

As a primary means of communication, the role of mobile telecommunications networks is important for a developing country's economic and social development. However, especially rural areas in low-income countries still lack mobile coverage. In the academic literature, only segmented solution strategies for this mobile coverage problem in rural areas are proposed. These are either technological, regulatory, or organizational solutions, whereas solving the mobile coverage gap requires an integrated approach to develop arrangements for mobile network rollout in rural areas. This paper presents a comprehensive overview of the causes of the lack of mobile coverage, the available solutions, and how they can be combined. Based on this overview, the paper proposes a decision support scheme for selecting a suitable arrangement for solving the mobile coverage gap. In this decision support scheme, the technical, organizational, and regulatory solutions are combined to develop a set of arrangements that match the local key causes of the lack of mobile coverage and that fit with the local context. In the last phase of the decision support scheme, the relevant stakeholders are involved in selecting the most suitable arrangement. We demonstrate the decision support scheme by applying it to the case of an unserved rural village in Indonesia, Unipa on the island of Papua, to show how it can guide a developing country to initiate the process of developing a solution for mobile coverage problems in rural areas.

1. Introduction

Growth in telecommunication penetration has been widely acknowledged as positively associated with human and economic development. A 10 % increase in mobile broadband penetration can increase GDP per capita by 0.81 % (Edquist et al., 2018). Many studies reveal a positive connection between telecommunication services and the human development index (Ejemeyovwi et al., 2019; Qureshi and Afzali, 2017).

Mobile telecommunication services play a crucial role in developing countries in which fixed telephony networks are under-developed, to cover the uncovered area and to leapfrog the fixed network. With its less expensive roll-out costs and the fixed-line penetration decline, mobile telecommunication is becoming the primary means of communication in developing countries (Arakpogun et al., 2017; Kefela, 2011; Loo and Ngan, 2012). As the primary means of communication, its role in developing countries' development is more significant than in developed countries. This makes equal distribution of mobile telecommunication networks very important for developing countries.

Developing countries are mainly composed of rural areas and the vast majority of people in low income countries live as rural populations (Anríquez and Stloukal, 2008; Bhuiyan, 2004). While the urban areas tend to be served by the most advanced technologies (such as the forthcoming 5G mobile networks) (Andrews et al., 2014), rural areas are more heavily exposed to the mobile coverage problem (Chiha et al., 2020). For example, in Indonesia in 2020, thousands of villages were still not covered by mobile telecommunication services and out of 3100 villages without mobile coverage, 3079 villages comprised <20 % built-up area (Ditdal PPL, 2021a). Without proper countermeasures put into place to reduce or solve the problem, the digital divide between the people living in urban areas and those living in rural areas will be exacerbated in the future. Therefore, it is important to explore how mobile network coverage in rural areas in a developing country is currently established and how to improve it.

So far, the academic literature only describes segmented solutions for the mobile coverage problem in rural areas, proposing either technological, regulatory or organizational solutions. Technological solutions use network architecture and/or specific equipment for addressing the

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problem, such as the unmanned aerial vehicle (UAV) (Chiaraviglio et al., 2019; Song et al., 2021), wireless long distance (WiLD) backhaul (Simo-Reigadas et al., 2015) and VillageCell solutions (Anand et al., 2012). In addition, the organizational solutions mentioned in the literature focus on the involvement of certain (new) actors, such as small rural operators (SRO) (Prieto Egido et al., 2020), mobile virtual network operators (MVNO) (Cricelli et al., 2011; Kiiski and Hämmäinen, 2004) and community-based networks (Barela et al., 2016; Heimerl et al., 2013; Salemink and Strijker, 2018). Other authors address regulatory solutions that emphasize coping with the problem of non-coverage by using governmental interventions in the form of new regulations or modifications of extant regulations and/or policies, such as coverage obligations (Cruz and Touchard, 2018; Sridhar and Prasad, 2011), universal service funds (USF) (Arakpogun et al., 2017), spectrum management (Touchard, 2017; Valletti, 2001), and the like. However, these separate solutions are not sufficient to solve the mobile coverage problem in rural areas. Technological solutions can only be effective if they match with the implemented organizational and regulatory solutions. For example, a technological solution cannot be implemented effectively if it is not allowed by local regulations (see e.g. (Heimerl et al., 2013)). This is an academic knowledge gap: none of the literature provides an overview of how to combine technological, organizational and regulatory solutions; let alone a comprehensive guidance on which combination of solutions is suitable for which (local) situation and what is required for its implementation.

We consider the lack of mobile telecommunication coverage in rural areas in developing countries as a complex socio-technical challenge in which technological, societal, business, and institutional components are involved. Solutions must address all these aspects. There are multiple and diverging actors' interests involved in managing the mobile telecommunications system and interdependencies between actors exist (Geels, 2004). Governments have a great interest in expanding mobile network services in rural areas as a way to improve the national economy, to maintain public values, and to improve institutional presence (Prieto Egido et al., 2020; Ubacht, 2020). In contrast, mobile network operators' interests can be primarily focused on commercial objectives such as return on investments and growth in market shares (Ubacht, 2020). These competing interests create tensions between private and public values in the mobile telecommunications market. National governments have an important role in and possess the instruments to improve the mobile network coverage. A solution for the mobile coverage problem can only be adequate and impactful if it accommodates the involved actors' preferences. However, none of the solutions we found in the literature considered the preferences of the relevant actors (such as market parties and public authorities) in the mobile telecommunication sector. This is a second academic knowledge gap.

All in all, what is missing in the academic literature is a comprehensive overview of all causes of the mobile coverage gap and of available (types of) solutions, and an integrated method for choosing specific solutions under specific circumstances, considering local characteristics and stakeholders' preferences. To address these academic knowledge gaps, this article has two research objectives. The first objective is to create an overview of the causes of the mobile coverage gap in rural locations and the different types of solutions to solve this gap, and how these solutions can be combined. The second objective is to develop an integrated method for governmental bodies for choosing specific mobile communication solutions under specific circumstances, considering local characteristics and stakeholders' preferences. To reach the first objective, we conducted an extensive literature review, to create an overview of the causes of the mobile coverage gap in rural locations and the different types of solutions to solve this gap, and how these solutions can be combined. To reach the second objective, we developed, based on our causes-solutions-combinations overview, a decision support scheme for selecting a suitable solution arrangement for solving the mobile coverage gap in a country or region. Both our overview of the causes of the mobile coverage gap, solutions that match these causes and possible solution combinations and our decision support scheme form an academic contribution.

The remainder of this article is organized as follows. In Section 2 we describe our research approach and research methods. Next, in Section 3 we present an inventory of the causes of the mobile coverage problem in rural areas, and in Section 4 the available solutions and how these solutions can be combined. In Section 5, based upon the previous sections, we present our decision support scheme to identify the most suitable solution arrangement to solve the mobile coverage gap in a rural area. In Section 6 we demonstrate the decision support scheme by applying it to an exemplary case of a rural village in Indonesia. We present a discussion of our findings, the research limitations, and subsequent future research topics in Section 7. Lastly, in Section 8, we provide a short conclusion and present the scientific and societal contribution of our findings.

2. Research approach

We followed a qualitative research approach that included the following phases. First, a literature review was conducted to analyze the key causes of the lack of mobile coverage in rural areas in developing countries. This literature review was performed in March 2021. In Scopus, the search terms used were 'mobile telecom coverage rural' for all search fields and 'digital divide' in the article title, abstract, and keywords. This yielded 79 scientific articles, which were scoped down to 64 by excluding non-relevant subject areas (arts, medi, agri, bioc, math, phys, psyc, eart, envi and nurs), after which a manual selection and snowballing were applied to select the 28 most relevant articles. The results of this literature review phase are presented in Section 3 and are reflected in the first step of the decision support scheme we developed.

A second literature review was conducted into potential solutions to solve the mobile coverage gap in rural areas in April 2021. This time we used the search terms 'mobile', 'coverage', 'rural', telecom* and ('solution' or 'solv*') and excluded non-relevant subject areas (bioc, eart, chem, immu and vete) in title, abstract and key words, which yielded 57 scientific articles. As this first search mainly resulted in technological solutions, we used a second search string to also explore non-technological solutions given our socio-technical perspective. For this, we used the search terms ('mobile and telecom*') and (govern* or polic* or regulat*) and we limited to 'soci' or 'busi' or 'deci' or 'econ' or 'arts' or 'psych' or 'mult' in title, abstract and keywords. This search yielded 88 scientific articles. Manual selection by reading the summaries of the articles resulted in a list of 33 relevant scientific articles which were supplemented with three scientific articles that were found on Research Gate via the snowballing technique. These 36 articles are the basis for Section 4 of this article and for steps 2 and 3 of the decision support scheme we developed. An overview of the selected articles from both literature searches is presented in Appendix A. In the Discussion section an underlying potential problem with scientific literature reviews, namely selection bias in published studies, is discussed.

Based on the two literature reviews we developed the decision support scheme for selecting a suitable arrangement for solving the mobile coverage gap. To demonstrate the use of the decision support scheme we applied it to a case in Indonesia for which we selected the underserved village of Unipa. In this part of the research, we interviewed six representatives from the Indonesian Ministry of Communications and Informatics (Kominfo) and two representatives from two mobile network operators that are active in Indonesia. These interviews were conducted online in the period May–June 2021. The stakeholders were interviewed to first evaluate a preliminary list of solution arrangements for Unipa village, which we compiled based on desk research. After the first evaluation, they assessed the selected solution arrangements on four pre-specified criteria: the feasibility of implementing the solution, its potential negative impacts, the requirements for achieving its objective, and the risks of the solution. This evaluation phase is reflected in step 4 of the decision support scheme and the demonstration of the decision support scheme is presented in Section 6 of this article.

3. Causes of lacking mobile coverage in rural areas in developing countries

As presented in Section 2 we conducted a literature review with 28 scientific articles to first make a comprehensive overview of all possible causes of the mobile coverage problem in rural areas in developing countries. This review is the basis for the first step of the decision support scheme which we present in full in Section 5 of this article. Based on our literature review we present the key causes of a mobile coverage gap in rural areas in the following paragraphs.

3.1. Commercial orientation of mobile network operators

The lack of coverage in rural areas is a consequence of a basic economic challenge exacerbated by the commercial orientation of mobile network operators (MNOs). Strong profit motives of the major MNOs limit their investments in rural connectivity because rural populations in developing countries have high poverty rates, making them an unprofitable customer segment (Prieto Egido et al., 2020; Cruz and Touchard, 2018; Galperin and Bar, 2007; Jha and Saha, 2016). This is also the case in developed countries, but refers more to mobile broadband services, not to basic mobile services, i.e. telephony and SMS (Salemink and Strijker, 2018; Prieger, 2013; Roberts et al., 2017; Townsend et al., 2013) as it stems from a higher level of general telecommunication penetration (Arakpogun et al., 2017). Moreover, MNOs in developing countries are less willing to invest in small communities in rural areas because of the high opportunity costs of deploying the network in urban areas (Trendov et al., 2018) and the high investments to maintain their market share in urban areas in which aggressive competition among operators occurs (Heimerl et al., 2013).

The commercial orientation of MNOs and the mobile communication industry's competitive environment are the results of telecommunication market liberalization and privatization enacted by the government. Shifting from a state-owned monopoly to a private industry is a typical trajectory of the telecommunication market industry in many countries (Arakpogun et al., 2017; Berg and Hamilton, 2002; Chavula, 2013; Gutierrez and Berg, 2000; Montenegro and Araral, 2020). In the beginning, as telecommunication services were considered an essential need of society, governments tried to assure its deliverance and performance via state-owned companies, which monopolized the sector throughout nations (Montenegro and Araral, 2020). However, as shown by studies in Bangladesh (Bhuiyan, 2004) and Africa (ITU, 1999; Minges, 1998; Whitehead et al., 2011), the limited technical expertise and investment capacity of the government led to low teledensity and left the telecommunication service performance much to be desired as the telecommunication needs grew. The state-owned telecommunication operators' bureaucratic structure increased management costs and placed a burden on the available funds (Bhuiyan, 2004). Due to these limitations, to extend telecommunication services to the unserved and underserved areas, governments in developing countries turned to the World Bank and other international bodies for support (Irwin and Brook, 2003; Sutherland, 2014; Wanjiku, 2014). At the heart of the conditions for granting these supports was the need to introduce reforms, including the mobile telecommunications sector's liberalization (Sutherland, 2014; Wanjiku, 2014). Other than that, liberalization and privatization were also the popular recommendations for reducing the government burden in service provision as it could attract foreign investments in the telecommunication sector and allow private entrepreneurs to contribute to network development (Bhuiyan, 2004). Although liberalization and privatization have increased access to mobile network services in countries worldwide, the services are still mainly limited to customers in urban areas.

3.2. Difficult topography, lack of energy grid and low road accessibility

The MNOs' profit motives are exacerbated by the difficulties for deploying networks in rural areas, such as the challenging geographical topography which makes them hard to be accessed, the lack of an energy grid to sustain the mobile network operations, challenging terrain types that hamper the mobile transmission signals (e.g., rainforests or mountains) and underdeveloped road networks (Prieto Egido et al., 2020; Heimerl et al., 2013; Touchard, 2017; Khaturia et al., 2020). These difficulties do not only hamper the deployment of network infrastructures but also drive up deployment costs. As investment in telecommunications infrastructure plays a major role in coverage expansion (Arakpogun et al., 2017; Hudson, 2006), coverage cannot be expanded without deep pockets and may be hindered if the investment costs are too high. Deploying infrastructure outside the urban and suburban areas can be twice as expensive as in rural areas (Cruz and Touchard, 2018; Rendon Schneir and Xiong, 2016; Tyler et al., 1995), whereas revenue opportunities can be as much as ten times lower (Cruz and Touchard, 2018; Touchard, 2017). The combination of high prices of deploying infrastructure and weak demand for mobile internet services from rural populations deeply affects the business case for MNOs to deploy network infrastructure and results in low mobile network coverage in rural areas.

3.3. Low population density

Townsend et al. (2013) and Wright (1995) consider digital connectivity as an essential measure against the depopulation of rural areas. The wide range of telecommunication services such as public e-services, e-learning, e-mail, telemedicine, and online social networking help rural areas to sustain themselves. Without these services, citizens will be pushed to move to cities where essential services can be found. Thus, the lack of telecommunication services in rural areas leads to urbanization, making rural areas less populated and hence less economically attractive for MNOs to provide their services (Cruz and Touchard, 2018; Jha and Saha, 2016; Wright, 1995). Without telecommunication services in rural areas, the digital divide between the urban and rural areas widens, and, subsequently, the rural population's poverty rates increase (Prieto Egido et al., 2020; Cruz and Touchard, 2018).

On the side of end users, low quality such as insufficient voice call quality and/or low data rates and issues of affordability because of relatively high prices of telecommunication services in rural areas can decrease the services' usage. The low usage means a low return on investment (RoI), hence low profit for the MNOs who become reluctant to maintain their existing networks in those areas.

3.4. Lack of local support

Surana et al. add that most of the deployed networks in rural areas do not stay operational over the long haul (Surana et al., 2008). Their study shows that MNOs encounter various challenges in maintaining the network in rural areas due to environmental issues, the locations' difficult accessibility, and power instability, leading to more frequent component failures and longer downtime. Subsequently, these situations increase the MNO's operational costs for traveling to the location to replace the components more often and decrease the revenues due to downtime. Consequently, sites in rural areas are abandoned. However, it turns out that MNOs' financial capacity is not the only thing that affects the sustainability of a site, but also the local support. Heimerl, et al. (Heimerl et al., 2013) found that if locals support a network establishment, they can help maintain and repair the network. We, therefore, label this cause as 'lack of local support'.

3.5. Lack of regulatory obligations

National governments can use regulatory obligations to stimulate the coverage of areas that are not attractive for mobile network operators with a commercial orientation. Solely relying on the market to close the gap will result in the exclusion of the unprofitable areas, whereas telecommunication services are essential for and should be equally provided to everyone (Bhuiyan, 2004). Regulatory obligations can take several forms. Spectrum license obligations can stipulate that the licensee is obliged to e.g., cover a certain percentage of the country or laws and regulations can be formulated to cover unserved areas. In addition, generic spectrum policy can be used to promote coverage in rural areas. Cruz and Touchard (Cruz and Touchard, 2018) suggest to stimulate the use of spectrum bands for frequencies below 1 GHz, which are considered ideal for rural areas as they can cover larger areas than bands with frequencies higher than 1 GHz with the same site configurations (height, power consumption, etc.), although they provide a lower data rate. According to the ITU, using 900 MHz allows operators to cover 2 to 2.7 more area than using 1800 MHz (Cruz and Touchard, 2018). As a result, operators will be able to cover more population at the same costs. Another approach in spectrum licensing regimes is presented by Sridhar and Prasad who mention that in India licenses are divided into 22 areas, which are categorized based on their revenue potential (Sridhar and Prasad, 2011). In each area, several 20 years licenses are issued to MNOs which include a roll-out obligation to cover a certain percentage of the area within a stipulated period. Compliance costs for these obligations can be counterbalanced by settling for a lower license price or installing related tax rules or the government can allow mobile network operators to agree upon infrastructure sharing arrangements to minimize investment costs in infrastructure components which are the most costly elements of the mobile network (Cruz and Touchard, 2018). Needless to say, that compliance with regulatory obligations has to be monitored and not having formal means to address non-compliance will lead to failure in reaching the objectives for rural coverage.

3.6. Synthesis of key causes of lacking mobile coverage in rural areas

Based on the literature review we summarize the key causes of lacking mobile coverage in rural areas in Table 1. Reflecting on these key causes we can state that some of them can be more or less influenced, e.g. the population density in a rural area is a given key cause and cannot be influenced. A low population density (5) has a major influence on the potential return on investment and is thus at odds with the commercial orientation of MNOs (1). This tension could potentially be solved by turning the mobile telecommunications service into a public service with huge public investments to service remote areas. However, due to the huge costs and the current trend of liberalizing the mobile telecommunications market this option is highly unlikely. Key causes 2, 3, 4 and 5 are highly related. Key causes 3 and 4 can be influenced but this would also require huge (public or private) investments.

3.7. Local context requires problem analysis

In addition to the key causes, our literature review also showed that the actual cause of lacking mobile coverage can vary between countries or even between rural areas within one country. For example, for Bangladesh, Bhuiyan (Bhuiyan, 2004) mentions that the telecommunication network failed to expand to rural areas due to a lack of government policy support, such as the absence of coverage obligations. On the other hand, Heimerl et al. (Heimerl et al., 2013) argue that in an Indonesian village the mobile coverage was lacking because of the absence of village-wide electricity and not having a terrestrial backhaul network around the village. These examples show that a problem analysis needs to be conducted to understand the actual cause (s) of the mobile coverage gap problem per country and rural area. Hence, this problem analysis step is the first step in the decision support scheme that we present in Section 5. But first, we present the potential solutions mentioned in the academic literature in the next section.

4. Solutions for mobile coverage problems in rural areas

Based on our second literature review (see Section 2 for the search strategy used) we found 21 solutions for solving the mobile coverage problem in rural areas. As argued in the Introduction section, technological solutions can only be effective if they are implemented in combination with matching organizational and regulatory solutions. Therefore, we analysed the literature for technological as well as organizational and regulatory solutions. These are summarized in Tables 2, 3, and 4 respectively in which the solution names, the key causes that the solution contributes to, as well as a summarized overview of the requirements and challenges as mentioned in the literature are given. In Table 5 we show which technological solutions can be combined with which organizational and regulatory solutions. We explain the contents of Tables 2–5 in the following subsections.

4.1. Technological solutions

The technological solutions as described in the scientific literature have the following sub-types:

Access technology: refers to the technology used to connect the network to the user, such as using a Femtocell, OpenBTS or an Unmanned Aerial Vehicle (UAV);

Backhaul technology: refers to the technology for connecting the site in rural areas to the core network, such as a fibre optical cable, wireless terrestrial or satellite link;

Power technology: specifies the type of power source such as solar power and the electricity grid;

Support technology: refers to any technology for the supporting system of the rural network, such as a battery maintenance system.

We provide short descriptions of the technological solutions as presented in the literature and listed in Table 2.

TUCAN3G is a mobile network architecture that uses unlicensed spectrum, using so-called femtocells for the access network in each settlement area. A wireless multi-hop backhaul is used to connect the access network to a core/national network. TUCAN3G has proven to be a low-cost solution for rural areas in Peru, covering 450 km distance to the core network (Prieto Egido et al., 2020; Martínez-Fernández et al., 2016; Rey-Moreno et al., 2011; Simó-Reigadas et al., 2019).

Satellites offer flexible connectivity, and any location can be covered, but the operational costs are high, and mobile services that require high transmission speed (such as video content) will suffer latency effects (Chiha et al., 2020; Wright, 1995; Borst et al., 2010; Philip et al., 2017; Wang et al., 2017). As alternative Chiha et al. propose a *cached GEO-satellite* solution to deliver broadband to rural areas in which the most popular content is cached in an edge network (Chiha et al.,

Table 1
Key causes of lacking mobile coverage in rural areas.

1. Mobile network operators' commercial orientation
2. Difficult topography
3. Lack of electricity grid
4. Low road accessibility
5. Low population density
6. Lack of local support
7. Lack of regulatory obligations

Table 2
Technological solutions.

No.	Solution name	Key causes addressed and how the solution addresses them	Requirements & challenges
1	TUCAN3G (access, backhaul and power) (Prieto Egido et al., 2020; Martínez-Fernández et al., 2016)–(Simó-Reigadas et al., 2019)	Low population density: femtocells and unlicensed terrestrial backhaul Lack of electricity grid: it can be operated with solar power Difficult topography: it can be used with high towers Line of Sight and to avoid interference Lack of local support: employing the local community to maintain and repair the network can foster a sense of responsibility for the maintenance of the network	Requirements (Local): • Between 400 and 1000 inhabitants in the targeted community. Public fund support is needed in case of a lower number of inhabitants, and femtocells would not be suitable when it is higher. • Suitable for rural regions that consist of several smaller settlement areas. • Local support to help maintain the network. Requirements (National): • Regulations that allow the use of Wi-Fi bands for backhaul transmission. In countries where it is forbidden, WiMAX is the only low-cost alternative. • Measures to protect the free-band backhaul link from interference • Measures to minimize the need to visit the location for maintenance Challenges: • Complex traffic and Quality of Service management.
2	Cached GEO-satellite (access, backhaul and power) (Chiha et al., 2020)	Low population density: caching the data traffic Low road accessibility: the use of satellite backhaul Difficult topography: the use of satellite backhaul	Requirements (Local): • Users' Willingness-to-Pay (WTP) around 19 euros per month • If macro-cell is used, 1050 users are needed for one tower (14 persons per sq. km). • Electricity grid for powering the radio access network and hardware • If macro-cell is used, the area should not be mountainous or in a rainforest
3	Unmanned Aerial Vehicle (UAV) (access, backhaul and power) (Chiaraviglio et al., 2019; Wang et al., 2017)–(Chiaraviglio et al., 2017b)	Low population density: UAV can be used that can target specific settlement areas, is easy to maintain and flexible, which results in a cost-effective investment Lack of electricity grid: it can be operated with solar power Low road accessibility: only simple network components can be used Difficult topography: aerial transceivers do not need towers	Challenges: • Ensuring the correct number of SPs, batteries, ground sites and UAVs, the optimum distance between the UAV and the ground site, UAV's trajectory, recharging schedule and interference management are essential to make the network economically feasible and well-perform • Development is still in an early phase which means that it is not available on the market yet
4	VillageCell (access and backhaul) (Anand et al., 2012)	Low population density: this solution can allow free of charge voice calls within the community Low road accessibility: simple network components can be used Difficult topography: a localized and small-scale network can be used	Requirements (Local): • Technically skillful personnel in the local community • Villagers that prefer local calls to long-distance ones and prefer voice calls instead of internet services Requirements (National): • Government permission to use GSM bands for its radio access and number blocks when VillageCell is run by a non-MNO. Challenges: • The network arrangement can be difficult to balance the routes due to the limited capacity of OpenBTS • If the electricity grid is absent in the area, further investigation is needed to identify a suitable power source
5	Store-and-Forward network (access) (Palazzi et al., 2011)	Low population density: providing one central point for all population to get service access without using MNOs investment as it utilizes the existing internet access point and public transportation infrastructure	Requirements (Local): • Public transportation or other routine transportation activities that can carry a Mobile Delay/ Disruption Tolerant Network (MDTN) server for collecting the data and exchanging it at the nearest internet access point
6	Solar power source (power) (Martínez-Fernández et al., 2016; Rey-Moreno et al., 2011; Kabir et al., 2018)–(Thakur et al., 2017b)	Lack of electricity grid: electricity can be generated in the absence of a power grid Low population density: reduction of operational costs per site in rural areas	
7	Battery performance prediction model (support) (Fan et al., 2016)	Low population density: reduction of maintenance costs per site and increase of the site's uptime Lack of electricity grid: improving the performance of the network by reducing battery issues	Challenges: • This solution is not off-the-shelf, which means that it is not available to purchase on the market
8	Ambient Network (support) (Grampín et al., 2007)	Low population density: traffic routing optimization can reduce the maintenance costs and backhaul rent fee per site	Challenges: • The algorithm is site-specific and not off-the-shelf, which means that it is not available to purchase on the market

Table 3
Organizational solutions.

No.	Solution Name	Key causes addressed and how the solution addresses them	Requirements & challenges
1	Community Cellular Network (CCN) (Prieto Egido et al., 2020; Barela et al., 2016)–(Salemink and Strijker, 2018; Rey-Moreno et al., 2011; Philip et al., 2017; Gieling, 2018; Wade, 2015)	Lack of local support: employing the local community to maintain and repair the network can foster a sense of responsibility for the maintenance of the network	Requirements (Local): • Technically skillful and resourceful personnel in the local community and/or in local governments Requirements (National): • Permission both from the MNO and the government to use MNO's unused frequencies • Regulations that allow the Community Cellular Network to interconnect to the existing networks • Mechanism or regulation to acquire support from local governments
2	Small Rural Operator (SRO) (Prieto Egido et al., 2020; Cruz and Touchard, 2018)	Low population density: a specific operator that is responsible to cover low density areas allows a significant reduction on network installation and maintenance costs	Requirements (National): • Public funds to support areas with insufficient revenue potential due to low population density or too difficult topography • A mechanism to accommodate private investment in rural areas that will be economically developed in the future Challenges: • Setting up initial agreements among MNOs and SROs might require a complex and time-consuming process • This solution can potentially lead to monopoly that can result in abuse of position and inefficient use of resources
3	MVNO in rural areas (Cricelli et al., 2011; Kiiski and Hämmäinen, 2004; Son et al., 2019)	Low population density: this solution can encourage innovation for new services targeted towards rural populations MNO's commercial orientation: an MVNO can play a role when an unprofitable part of the MNO network risks being taken down. In this situation an MVNO can develop special services on the MNO network that can lead to new revenues.	Requirements (National): • Consent from extant MNOs for network access Challenges: • An MVNOs existence can lead to the decline of revenues for the MNO, which can be a barrier for negotiating access to the MNO network • Negotiations for access with MNOs can be difficult as MVNOs may take over their users
4	Central and local authority's support (Cruz and Touchard, 2018)	MNO's commercial orientation: by reducing the MNO's overall expenditures Lack of local support: by increasing the involvement of the local government	Requirements (National): • The central authority should provide guidelines to local authorities regarding mobile network deployment or should apply mechanisms to incentivize local governments to voluntarily adopt the central authority's guidelines • The central and local governments need to conduct a preliminary assessment on the actual hurdles that MNOs face when seeking local permits

2020). This solution has a high electricity demand which is difficult to match with solar energy.

A mobile network architecture based on *Unmanned Aerial Vehicles* powered by solar energy can provide 5G coverage in rural areas (Chiaraviglio et al., 2019; Wang et al., 2017; Chiaraviglio et al., 2017a; Chiaraviglio et al., 2017b; Ilcev and Singh, 2004). This is a low-cost solution and the coverage can be more precisely targeted at where the citizens live in the wider rural area. The use of UAVs is still in an early phase of development.

VillageCell is a low cost and technically simple community cellular network based on open-source software (OpenBTS) which can be maintained by the community itself. It mainly provides for intra-community communications with free voice calls, enabling citizens with low income to make calls. A satellite backhaul can provide for using voice over internet connections such as Skype (Anand et al., 2012).

A *Store-and-Forward network* provides free e-mail and internet services using a server installed on e.g., a public transportation vehicle that passes the unserved villages regularly. The village resident sends an email to the server, the email is transmitted to a core network in a connected village once the public transportation vehicle passes by. Subsequently, the answer is transmitted to the village resident once the vehicle passes the unserved village again (Palazzi et al., 2011).

MNOs are usually unwilling to set up a mobile network if the site location lacks a stable power source because network downtime leads to a loss in revenues and higher maintenance costs of the network. Several studies show that it is feasible to use *solar power* for the operation of a mobile network, especially when femtocells are used and during the daytime (Martínez-Fernández et al., 2016; Rey-Moreno et al., 2011; Kabir et al., 2018; Thakur et al., 2017a; Thakur et al., 2017b). Using batteries to store the daytime solar power can improve operations during the night as well.

Another means to prevent downtime due to power failure is to use a *battery performance prediction model* as suggested by Fan et al., which enables MNOs to schedule maintenance and replacement (Fan et al., 2016). This improves the availability of the mobile network services, prevents the loss of revenues and lowers the operational costs for MNOs by reducing site visits for repairs.

The last solution found in our literature review is using an *ambient network* for the last mile. This support technology uses an algorithm that acts autonomously in routing traffic between (WiFi/GSM) mesh network nodes and has a self-healing function in case of failing nodes (Grampín et al., 2007). This solution lowers the costs for network operations in rural areas.

In Table 2 a summary of the technological solutions is provided, including for which key causes of lacking mobile coverage the solution can be used and by which means, and the related requirements and

Table 4
Regulatory solutions.

No.	Solution name	Key causes addressed and how the solution addresses them	Requirements & challenges
1	Coverage obligated spectrum license (Cruz and Touchard, 2018; Sridhar and Prasad, 2011)	Low population density: by applying coverage obligations for specific areas Lack of regulatory obligations: by applying coverage obligations MNOs will be enforced to cover economically less attractive areas	Requirements (National) • The spectrum price needs to be adapted to compensate for the compliance costs • Sanctions need to be in place for non-compliance Challenges: • There is no exact rule to define the right spectrum price
2	Spectrum management (Cruz and Touchard, 2018)–(Valletti, 2001; Son et al., 2019)–(McDowell and Lee, 2003)	MNO's commercial orientation: by reducing the MNOs overall expenditures	Requirements (National): • Competition assessment and stakeholder consultation need to take place before neutralising the spectrum's technology to ensure a positive long-term effect on the market. • Spectrum trading needs to be monitored to avoid hoarding and anti-competitive behaviour Challenges: • MNOs may not want their 'spectrum repository' to be known by their competitors. • Changing the licensing regime is not easy
3	Taxation policy to foster investments in rural areas (Cruz and Touchard, 2018; Touchard, 2017)	MNO's commercial orientation: by reducing the MNOs overall expenditures	–
4	Infrastructure sharing (Cruz and Touchard, 2018; Touchard, 2017; Montenegro and Araral, 2020)	MNO's commercial orientation: infrastructure sharing can increase the profitability per rural site and reduce the MNOs' overall expenditures Lack of regulatory obligations: by monitoring the practical aspects of infrastructure sharing and taking away barriers	Challenges: • Design and implementation of this solution are complex and requires technical capacity and political will • Compliance policy needs to be developed to encourage network sharing, while preventing loss of competition, the risk of sensitive information exchange and collusion at the service level
5	Universal Service Fund (USF) (Arakpogun et al., 2017; Cruz and Touchard, 2018)	Low population density: lowering MNOs' deployment costs in rural areas with low population density	Requirements (National) • A good oversight mechanism, stakeholder involvement and transparency. • Independent and skillful USF administrators to address the technical, economical, and legal aspects • Pre-defined USF targets considering the actual market needs. Challenges • USF might be ineffective if excessive bureaucracy is applied for the allocation of funds
6	Public subsidy on rural network development (Cruz and Touchard, 2018; Wright, 1995; Philip et al., 2017)	Low population density: lowering MNOs' deployment costs in rural areas with low population density	Requirements (National) • Transparent public allocation process for subsidies • A subsidy cannot stand on its own as a solution; it is merely an enabler for other measures. So, subsidies need to be paired with other solutions such as e.g. satellite or community-led initiatives.
7	Relaxing the Quality of Service (QoS) standard for rural networks (Touchard, 2017)	Low population density: by reducing the MNOs operational costs by differentiating the QoS requirements between rural versus urban areas. Lack of regulatory obligations: by adapting the regulation of QoS obligations	Requirements (National) • Clear indication of the rural areas that are eligible for relaxation • Regular evaluation to assess whether the relaxation can be lifted. Challenges • Strict QoS may create reluctance from MNOs to deploy networks according to their obligation as they are afraid to be penalized for the lower QoS. • This solution may well decrease the quality of the mobile service.
8	Information management system platform about network coverage (Touchard, 2017)	Lack of regulatory obligations: the information on network coverage can be used by the regulator to discuss the coverage obligation with the MNOs	Requirements (National): • Reliable and up to date data from independent sources
9	Direct public investment in critical enabling national infrastructure (Touchard, 2017)	Low population density: public investments into fibre optic backbone networks, electricity grid and road access will potentially reduce the network deployment costs Lack of electricity grid: via public investment into power grids Low road accessibility: via public investment in road improvements	Requirements (National): • Significant public capital investments and coordination between different Ministries is needed

challenges for implementation.

4.2. *Organizational solutions*

Looking for organizational solutions as presented in the literature, we found four solutions to address the causes of lacking mobile coverage (see Table 3):

A *Community Cellular Network* (*CCN*) that is run by the local

Table 5
Solutions for each key cause of lacking mobile coverage.

Key cause of lacking mobile coverage	Solution type	Solution name
MNO's commercial orientation	Organizational	MVNO in rural areas
		Central and local authority's support
	Regulatory	Spectrum management
		Taxation policy that fosters investments in rural areas
		Infrastructure sharing regulation
Difficult topography	Technology	TUCAN3G
		Cached GEO-satellite backhaul
		Unmanned Aerial Vehicle (UAV)
		VillageCell
Lack of electricity grid	Technology	TUCAN3G
		UAV
		Solar power source
		Battery performance prediction model
	Regulatory	Direct public investment in critical enabling national infrastructure
Low road accessibility	Technology	Cached GEO-satellite backhaul
		UAV
		VillageCell
	Regulatory	Direct public investment in critical enabling national infrastructure
Low population density	Technological	TUCAN3G
		Cached GEO-satellite backhaul
		Unmanned Aerial Vehicle (UAV)
		Village Cell
		Store and Forward network
		Solar power source
		Battery performance prediction model
		Ambient Network
	Organizational	Small Rural Operator (SRO)
		MVNO in rural areas
	Regulatory	Coverage obligated spectrum license
		Universal Service Fund
		Public subsidy for rural network development
		Relaxing the QoS standard for rural networks
		Direct public investment in critical enabling national infrastructure
Lack of local support	Technological	TUCAN3G
	Organizational	Community Cellular Network (CCN)
		Central and local authority's support
Lack of regulatory obligations	Regulatory	Coverage obligated spectrum license
		Infrastructure sharing regulation
		Relaxing the QoS standard for rural networks
		Information management system platform on network coverage

community instead of a national Mobile Network Operator (MNO) can be a cost-efficient way to cover an unserved area. It does require technically skillful and resourceful personnel in the local community and/or local governments. In addition, local use of frequencies and interconnection with other networks need to be arranged. Profits from the services can remain within the local community and vandalism and theft of the hardware will diminish when locals take up the shared responsibility for maintenance of the CCN. However, the initial costs for setting up the network requires deep pockets (Prieto Egido et al., 2020; Barela et al., 2016; Heimerl et al., 2013; Salemink and Strijker, 2018; Rey-Moreno et al., 2011; Philip et al., 2017; Gieling, 2018; Wade, 2015).

Allowing a *Small Rural Operator* (SRO) to operate in rural areas with low population density and low return on investments has the advantage of having more expertise in how to operate a local network in an efficient way. In this case, the SRO network and the MNO network (s) will be connected so users of the two networks can communicate with each other. The MNO pays the SRO for local traffic generated on its core network. SROs are the only operator in their area; therefore, they do not have the compete with others (Prieto Egido et al., 2020; Cruz and Touchard, 2018). If revenues are insufficient, government subsidies may be needed.

A *Mobile Virtual Network Operator* (MVNO) can play a role when an unprofitable part of the MNO network risks being taken down. In this situation an MVNO can develop special services on the MNO network that can lead to new revenues. The MVNO pays for access to the MNO network to offer these services (Cricelli et al., 2011; Kiiski and Hämmäinen, 2004; Son et al., 2019).

The last organizational solution is for *central and/or local governments* to support MNOs to cover the unserved area. Although MNO's licenses are allocated at the national level, the MNOs must also comply with local rules when rolling out their networks. When local rules are too strict or complex or require lengthy permit processes, the MNO may refrain from covering the local area. Therefore this organizational solution can lead to a reduction of administrative costs for the deployment of new sites and can thus improve the conditions to roll out a network in a rural area (Cruz and Touchard, 2018).

In Table 3 a summary of the organizational solutions is presented, including for which key causes of lacking mobile coverage the solution can be used and by which means, and the related requirements and challenges for implementation.

4.3. Regulatory solutions

A final set of solutions mentioned in the literature are the regulatory solutions that can improve the mobile coverage in rural areas (see Table 4). These solutions need to be applied by governments to stimulate the coverage of rural areas. *First, the national government can formulate requirements for coverage* in the spectrum licenses that are allocated to MNOs. For example, the license may contain the obligation to cover a specific percentage of an area or even specific geographical areas within a set time period after the start of the network operation. These obligations can be counterbalanced by a lower price for the license (Cruz and Touchard, 2018; Sridhar and Prasad, 2011).

Another regulatory solution is related to *spectrum management*. Timely making sufficient spectrum bands available (especially in the lower spectrum which allows for wider coverage) and not asking unrealistically high prices for licenses may stimulate the roll out of mobile networks in more areas (Cruz and Touchard, 2018; Sridhar and Prasad, 2011; Touchard, 2017; Valletti, 2001; Son et al., 2019; Lun et al., 2019; McDowell and Lee, 2003). Active reallocation of frequencies from e.g., television to mobile services can also be used (Sridhar and Prasad, 2011) or technology neutral spectrum allocation in which operators may themselves choose which technology to use, as well as allowing for spectrum trading and sharing among operators (Cruz and Touchard, 2018).

Taxation policy can be used to foster investments in uncovered areas, e.g., taxing revenues rather than profits can discourage investment and innovation (Touchard, 2017) and taxes on network equipment e.g., via import taxes increase equipment costs. These taxes may harm the willingness to invest in network expansion to rural areas (Cruz and Touchard, 2018; Touchard, 2017).

Allowing for *infrastructure sharing* can lower the investment costs of MNOs as it minimizes the duplication of expensive infrastructure. Several components of a mobile network can be shared, such as antennas, sites and spectrum. In addition, national roaming can enable users to use a network from another provider when visiting an area not served by their own MNO (Cruz and Touchard, 2018; Touchard, 2017; Montenegro and Araral, 2020).

A *Universal Service Fund* (USF) which is fed by levies from extant MNOs can be used to allocate funding for the roll out of mobile networks in specified areas with low potential revenues and high deployment costs (Arakpogun et al., 2017; Cruz and Touchard, 2018).

Another financial arrangement is to use *public subsidies for rural network development* from the government in the form of monetary grants or incentives such as tax rebates for investments in rural areas or using satellite communications for connecting remote areas or exemptions for import duties for last-mile network equipment (Cruz and Touchard, 2018; Wright, 1995). Philip et al. add that these kinds of subsidies are often matched with other policy measures (Philip et al., 2017).

Regulators can also relax the *Quality of Service* (*QoS*) standards for rural networks so MNOs do not have to comply with the same rules for network availability and service quality in rural areas as for urban areas (Touchard, 2017). This can lower their network investment costs, but it will also result in lower service quality. Hence, regular evaluation is needed to assess whether the relaxation can be lifted.

Reliable data on network coverage is crucial to assess the state of affairs in mobile networks. To this end regulators can develop an information management system platform about network coverage that is not only based on data provided by the MNOs but also based on regular independent assessments. MNOs can profit from the information management system for avoiding network redundancies (Touchard, 2017).

The last regulatory solution from the literature refers to the use of direct public investments for critical enabling national infrastructure such as fibre optic backbone networks, the electricity grid and to enhance road accessibility (Touchard, 2017). These are more indirect measures to make the rural area more attractive for mobile network investments. Apart from considerable public capital investments, this solution requires coordination between different ministries (Touchard, 2017).

In Table 4 a summary of the regulatory solutions is provided, including which key causes of lacking mobile coverage the solution can be used and by which means, and the related requirements and challenges for implementation.

4.4. Synthesis of available solutions

After having shown the technological, organizational and regulatory solutions separately, we combined them. The outcome can be seen in Table 5. Our starting point in this table is the key causes for lacking mobile coverage. In Tables 2–4 the starting points were the solutions but the relevant key causes addressed by these solutions are mentioned in column 3 of Tables 2–4. So, we put the key causes from the third columns of Tables 2–4 to the left of Table 5, the solution types (technological, organizational and regulatory) in the middle and the solutions names from the second column of Tables 2–4 to the right. In this way, we show how for each key cause, certain combinations of solutions can be used to address this key cause and solve the mobile coverage gap.

5. The decision support scheme

In the previous sections, we presented an overview of the causes (Section 3), solutions and combinations of solutions (Section 4). Based on this overview, we developed an integrated approach to identify the most promising solution arrangement for the mobile coverage problem in a specific rural area. This approach has the form of a decision support scheme (DSS) as presented in Fig. 1. Our main envisaged users of this DSS are national and regional governmental bodies. The objective of the DSS is to identify and select the most suitable arrangement for a specific rural area or village, which combines technological, organizational, and regulatory solutions and also includes a stakeholder assessment regarding the feasibility, the negative impacts, the requirements, and risk assessment (as elaborated on in Section 6).

The DSS consists of four main steps:

1. Identification of the causes of the mobile coverage gap in a particular local context;
2. Collecting all solution options;
3. Developing the solution arrangement;
4. Stakeholder assessment.

In the following paragraphs, we describe these steps in more detail.

5.1. Step 1: identification of the causes of the mobile coverage gap in a particular local context

This first step starts from the comprehensive overview of the causes of the mobile coverage gap as described in Section 3 which must now be specified for the particular local context under consideration. This is shown in the first step of Fig. 1. The identification of the causes leads to

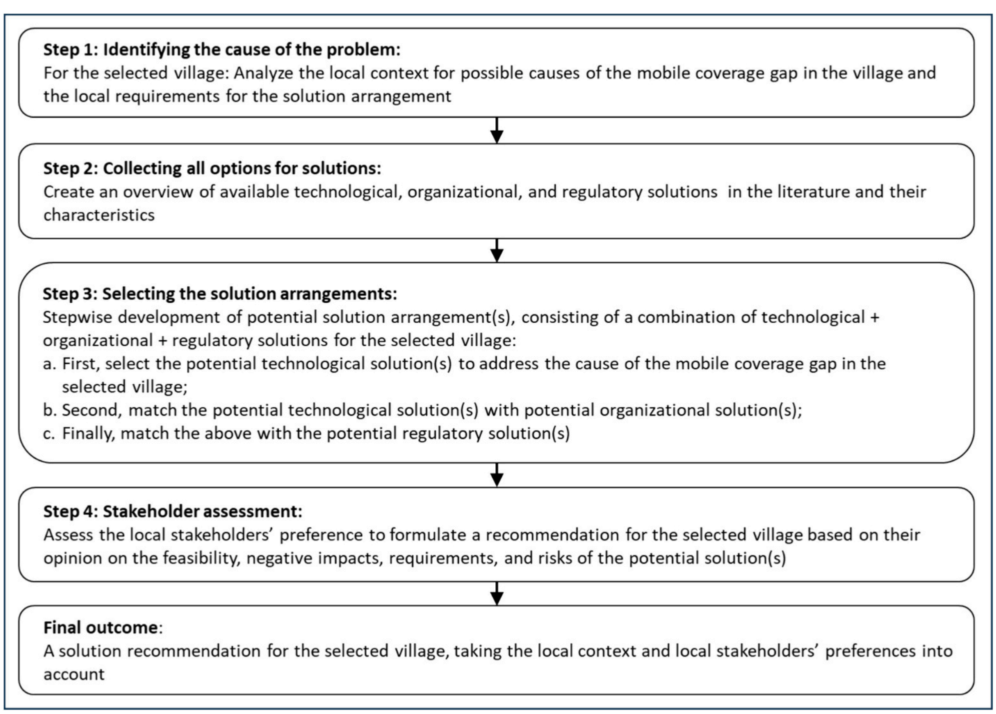

Fig. 1. The decision support scheme (DSS) for governmental bodies to select a suitable arrangement for solving the mobile coverage gap in a local context.

the key factors that, by themselves or together with other factors, induce the mobile coverage problem in a specific rural area.

5.2. Step 2: collecting all solution options

This step is described in Section 4 and represented in the second step in Fig. 1. The inventory of the solutions is done by reviewing the state of the art in literature. For now, we consider the available and applicable solutions as listed in Tables 2, 3 and 4 in Section 4 up to date. However, for future efforts, we suggest that the literature review for the inventory of available technological solutions is revisited to fit with the state of the art in technological innovation in mobile networks and services. This step results in a list of possible solutions offered for solving the mobile coverage problem in rural areas. These solutions can be categorized into technological (see Table 2), organizational (see Table 3), and regulatory solutions (see Table 4).

5.3. Step 3: developing the solution arrangement

The actual implementation of a solution requires the development of an arrangement in which the technological, the organizational and the regulatory aspects involved are all taken into consideration. This is represented in the third step of Fig. 1. The subsequent activities are:

3a: selection of a limited number of technological solutions that match with the local key causes of the lack of mobile coverage and that fit with the local context. Technological solutions are selected first and become the foundation for constructing the solution arrangement because the local context defines the possible technological solution (s). The technological aspect refers to the technical aspects of the network deployment, i.e., the choice of the access technology, the backhaul technology, the power technology, and the passive infrastructure components (these are the basic required elements of a mobile network);
3b: selection of organizational solutions that match these technological solutions and that fit with the local context. The technological solutions can only be executed by a specific actor and/or require the involvement of certain actors. Hence, the organizational aspect pinpoints to the required and suitable actor(s) to roll out the technological solution;
3c: selection of regulatory solutions that match with the technological and organizational solutions and fit with the local context. Regulatory adjustments or new regulations may be required for implementing a particular solution by a certain actor or actors. Therefore, the regulatory aspect completes the arrangement to ensure the development of a comprehensive solution arrangement.

The outcome of step 3 is a limited number of solution arrangements that consist of a combination of a technological solution, an organizational solution, and a regulatory solution.

5.4. Step 4: stakeholder assessment

The last step of the DSS requires the involvement of the relevant stakeholders' assessment of the selection of the arrangements for solving the mobile coverage problem in rural areas, as represented in the fourth step in Fig. 1. After the technological, organizational and regulatory solutions have been arranged into optional arrangements for the local situation, these need to be evaluated by the relevant stakeholders. After all, if the stakeholders disagree with the solution arrangement, implementing it will be difficult, if not impossible. This stakeholder assessment can be performed in different ways. We propose a two-phase evaluation. In phase 1, the stakeholders are asked to rank the solution arrangements on criteria of their own preference. In phase 2, they are asked to dive deeper into the 'top two' solution arrangements and for these to reflect on a number of pre-specified criteria: feasibility, negative impacts, requirements and risks of the solution arrangement. Ideally, a broad range of relevant stakeholders is involved in this stakeholder assessment step. Now that the DSS is explained, we demonstrate its use by applying it to a case in the next section.

6. Demonstration of the decision support scheme

We use a case from Indonesia to demonstrate our DSS. According to the mobile network coverage data (CovData) of the Indonesian Ministry of Communication and Informatics (Kominfo), 3100 villages out of a total of 83,285 villages and sub-districts in Indonesia were completely unserved by a mobile network (Dital PPL, 2021b). This CovData set consists of the information about the 2G, 3G and 4G coverage level (in square meters) in each village and sub district in Indonesia captured in the second quarter of 2020. In CovData an unserved village is defined as a village with 0.00 km^2 2G, 3G and 4G coverage of its settlement area and <50 % coverage of its land area. Almost all unserved villages have <30 % settlement area and are located outside the islands of Java and Bali, which are the two most densely populated and economically most developed islands in Indonesia. With the target of having 9.5 % of its GDP in 2025 from the digital economy (Yasyi, 2020), solving mobile telecommunication coverage gaps in rural areas becomes crucial for Indonesia. Our DSS can support the Indonesian stakeholders to address this concern. Therefore, we demonstrate how the DSS can be used by applying it to the actual case of an unserved rural village in Indonesia.

We selected the unserved village of Unipa on the Indonesian island of Papua. This village is representative for many other villages in Indonesia, having a low population density and located in a mountainous area. In the next paragraphs we follow the steps as illustrated in Fig. 1 to develop and assess a solution arrangement to provide mobile coverage for Unipa.

6.1. Step 1: identification of the causes of the mobile coverage gap

Unipa village can be categorized as a rural area since its total population is 797 (Dukcapil, 2016). The settlement area of this village is 0.07 km^2 while the total area of the village is 530.45 km^2 (Ditdal PPL, 2021a). Hence, the population density in Unipa village is only 1.5 persons per km^2. A fibre optic line passes through the village, and there are two 4G sites around 30 km from the village that are owned by BAKTI, the Indonesian Telecommunications and Information Accessibility Agency.[1] The topography of Unipa village is mountainous: the contour map of Unipa village area provided by Google Earth shows that Unipa village ranges from <100 m to around 3000 m above sea level. The accessibility to Unipa village and its electricity availability are relatively good. The village is accessible via both water and land routes from its nearby villages, and the land road can be traversed by four- or more-wheeled vehicles throughout the year (Tekno Nusantara Kapital, 2020). More than 83 % of the residents use electricity. The national Indonesian grid operator PLN's electricity grid has served the village since 2017 (Suroso, 2017). Taking the village's conditions into account, the key causes of the mobile coverage problem in Unipa seem to be the low population density and its difficult topography.[2]

6.2. Step 2: collecting all solution options

Based on our literature review we collected all solution options, as

[1] BAKTI is an organizational unit within the Ministry of Communication And Informatics with "the task of carrying out the management of universal service obligation financing and the provision of telecommunications and informatics infrastructure and services" (BAKTI, n.d.).

[2] We intentionally do not address the key cause 'lack of local support' as we were not able to interact with the local community and thus not able to assess this aspect. We reflect on this limitation in the discussion section.

presented in Table 5. These were up to date at the moment of our research (April 2021) but may have to be updated when using the DSS in the future, as in particular new technological solutions may arise based on innovations in mobile technologies.

6.3. Step 3: developing the solution arrangement

The development of the solution arrangement for this case follows the steps presented in Fig. 1 as described in detail in Section 5.3/Step 3: Developing the solution arrangement.

6.3.1. Step 3a: selection of technological solutions

The first step is the *selection of a limited number of technological solutions* that match the local key causes of the lack of mobile coverage and that fit with the local context. Based on the previous cause analysis, we see that Unipa is serviced by PLN's electricity grid and has relatively good road accessibility. As the state of the electricity grid and road accessibility are not the key cause of the mobile coverage problem in Unipa, any technological solution that only addresses a 'lack of electricity grid' or 'low road accessibility' should not be chosen as the solution (see Table 5). Hence, we select the potential technological solutions listed for the key factors 'low population density' and 'difficult topography'. These are: the battery performance prediction model, cached GEO-satellite backhaul, Store-and-Forward network, TUCAN3G, UAV and VillageCell (as described in Table 2).

To match these available solutions with the Indonesian local context we evaluated each one of them against location-specific requirements. This leads to the following considerations:

1. the *cached GEOsat backhaul* (see Table 2, solution 2) is not feasible in view of the requirements: the village has <1000 inhabitants and the area is mountainous (Chiha et al., 2020). In addition, the option of a satellite backhaul might not be cost-effective and preferred because there is already a fibre optic line passing the village;
2. the *Store-and-Forward solution* (see Table 2, solution 5) does not fit as there is no regular public transportation that can carry the required server from the village to the nearest internet access point (municipality centre or a mobile network site) for the transfer of messages;
3. as the village is well served by PLN's electricity grid, the solution of *solar power* does not apply to Unipa (see Table 2, solution 6)
4. the *Ambient Network* solution is not fitting with a situation in which the basic mobile infrastructure is not present yet as in the case of Unipa village (see Table 2, solution 8).

To conclude, the remaining feasible technological solutions for Unipa village are the use of TUCAN3G, UAV, VillageCell, and the battery performance prediction model (see Table 2, solutions 1, 3, 4, 7 respectively). As the battery performance prediction model is a supporting solution, we combine it with the three access and backhaul solutions as follows (see Fig. 2):

Option 1: TUCAN3G + battery performance prediction model
Option 2: UAV + battery performance prediction model
Option 3: VillageCell + battery performance prediction model

In the following paragraphs, we discuss these solutions one by one to arrive at the ultimate choice. We refer to Table 2 for the description of the key factors of the mobile coverage gap addressed and the measures to address them as well as the requirements and challenges for each solution.

6.3.1.1. Option 1: TUCAN3G + battery performance prediction model.

With Option 1 the TUCAN3G solution is adopted: femtocells (which are part of TUCAN3G) can be used as the radio access technology, which fits with Unipa's low population density. Unipa village does not need to employ solar power as it already has an electricity grid, nor set up a chain of wireless point-to-point links, neither use a high tower as an optical line cable is available and the area contains highlands. The availability of the electricity grid and fibre optic cable may further reduce the deployment costs of the network than what Prieto Egido et al. suggest for the deployment of TUCAN3G (Prieto Egido et al., 2020). The required unlicensed terrestrial backhaul can be included in Option 1 to

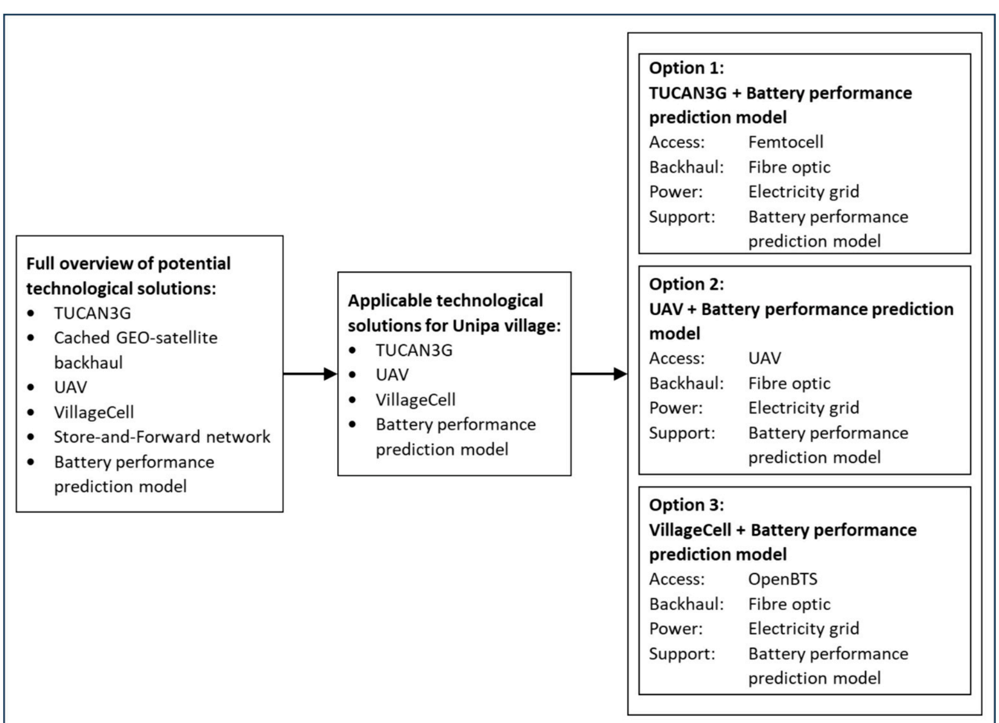

Fig. 2. Selection process of the technological solutions for Unipa village (Step 3a).

extend the network from Unipa village to its surrounding nine unserved villages. Extending the network to the surrounding unserved villages can potentially make the deployment and operational costs lower and allows for more profitability of the established network due to an increased number of users. The battery performance prediction model is included to minimize network down time due to battery failures.

6.3.1.2. Option 2: Unmanned Aerial Vehicle (UAV) + battery performance prediction model. Option 2 is based on the solution as suggested by Chiaraviglio et al. who present the use of Unmanned Aerial Vehicles (UVA) as mobile base stations for cellular connectivity (Chiaraviglio et al., 2019). This solution is less cost-intensive than using fixed mobile base stations and offers more flexibility in determining the area to be covered. Their suggestion to use solar panels is not necessary in the case of Unipa village, as explained above, so the initial capital costs will be lower than those calculated by Chiaraviglio et al. (Chiaraviglio et al., 2017b). Option 2 also uses a battery performance prediction model to minimize the revenue loss due to battery failures.

6.3.1.3. Option 3: VillageCell + battery performance prediction model. The last technological solution is based on the use of VillageCell with OpenBTS as its main technology, which is suitable given Unipa's low population density. VillageCell emphasizes small-scale and local communication, it enables free voice calls and SMS communication within Unipa village and with its nine surrounding unserved villages. The battery performance prediction model is included in Option 3 to increase the network's uptime and to minimize the need for maintenance.

6.3.2. Step 3b: selection of organizational solutions

After the selection of the feasible technological solutions for Unipa village, the development of the solution arrangement is continued with the *selection of organizational solutions* that match with these technological solutions and that fit with the local context.

6.3.2.1. Option 1: TUCAN3G + battery performance prediction model. Option 1 employs TUCAN3G and the battery performance prediction model. The requirements for implementing these solutions are (see Table 2): 'measures to protect the free-band backhaul link from interference' and 'measures to minimize the need to visit the location for maintenance'. These requirements imply the need for local support.

As the organizational solutions a Mobile Network Operator (MNO) or a Small Rural Operator (SRO) are considered the most feasible actors to implement the TUCAN3G solution. MNO and SRO are both present in Indonesia and can deploy the network by themselves. Other actors are not considered feasible as, according to Indonesian regulatory rules, neither the central or local authority nor a Mobile Virtual Network Operator (MVNO) have the formal authority to take up this leading role of network operator for TUCAN3G. Furthermore, a Community Cellular Network (CCN) is not feasible as at the time of our research it was not yet accommodated in Indonesia due to regulatory constraints.

6.3.2.2. Option 2: Unmanned Aerial Vehicle (UAV) + battery performance prediction model. UAV has similar requirements as TUCAN3G, so it also needs local support. Therefore, the same organizational solutions are suitable for Option 2: an MNO or SRO can take the lead in initiating the solution.

6.3.2.3. Option 3: VillageCell + battery performance prediction model. Option 3 employs a combination of VillageCell and the battery performance prediction model. For VillageCell, the requirement is that the local community prefers communication within the village and with neighboring villages (see Table 2). This will not be an attractive business case for an MNO. Therefore, an SRO is the most likely organizational option for setting up the VillageCell solution. As BAKTI owns the two 4G sites in the Unipa village area, BAKTI can support the implementation by negotiating with an MNO to allocate part of their spectrum for the VillageCell solution.

So far, the combination of the technological and organizational solutions for Unipa are:

- TUCAN3G + battery performance prediction model by an MNO
- UAV + battery performance prediction model by an MNO
- TUCAN3G + battery performance prediction model by an SRO
- UAV + battery performance prediction model by an SRO
- VillageCell + battery performance prediction model by an SRO

6.3.3. Step 3c: selection of regulatory solutions

The next step in the DSS is to consider the regulatory aspects required to implement the solution (see Table 4). When an MNO is selected as organizational solution, Cruz and Touchard suggest to give a Quality of Service (QoS) relaxation on the MNO's rural network and sectoral tax reduction proportional to the rural network investments for the MNO, which fosters investments in the rural solution (Cruz and Touchard, 2018). When an SRO is selected as organizational solution, this requires the matching of a Universal Service Fund (USF).

Table 6 summarizes the potential full arrangements in which the technological, organizational, and regulatory solutions for Unipa village are combined.

6.4. Step 4: stakeholder assessment

In the last step of the DSS a stakeholder assessment is performed in which relevant stakeholders' opinions and preferences are used to filter the (in this case 5) potential arrangements. The objective of this step is to select the most feasible arrangement that matches the preferences of relevant stakeholders best. We interviewed six representatives from the Indonesian Ministry of Communications and Informatics (Kominfo) and two representatives from two mobile network operators that are active in Indonesia. See Section 2 for the research method used in this step.

6.4.1. Stakeholder preferences for arrangements

The six interviewees were first asked to rank the five arrangements for Unipa village as presented in Table 6. The interviewees were free to choose any evaluation criteria for their rankings. The interviewees' rankings can be found in Table 7. By calculating the sum of the ranks given by all interviewees for each arrangement, the overall ranking was

Table 6
Potential arrangements for Unipa village.

Arrangement	Technological	Organizational	Regulatory
1	TUCAN3G + battery performance prediction model	MNO	Relaxing the QoS standard for rural networks + a taxation policy that fosters investments in rural areas
2	UAV + battery performance prediction model	MNO	Relaxing the QoS standard for rural networks + a taxation policy that fosters investments in rural areas
3	TUCAN3G + battery performance prediction model	SRO	Universal Service Fund by BAKTI
4	UAV + battery performance prediction model	SRO	Universal Service Fund by BAKTI
5	VillageCell + battery performance prediction model	SRO	Universal Service Fund by BAKTI

Table 7
Interviewees' preferences ranking of the solution arrangements for Unipa village.

Arrangement	IV 1	IV 2	IV 3	IV 4	IV 5	IV 6	IV 7	IV 8	Total score	Overall ranking
1	2	1	3	2	2	2	4	2	18	2
2	4	4	4	4	5	5	5	5	36	5
3	1	2	1	1	1	1	1	1	9	1
4	3	5	2	5	4	4	2	4	29	4
5	5	3	5	3	3	3	3	3	28	3

elicited. The arrangements with the higher sums have a lower overall ranking, this shows that arrangements 3 (sum = 9) and 1 (sum = 18) are the two most preferred arrangements for Unipa village. The difference between the second most preferable and the third arrangement (sum = 28) is considerable, therefore only arrangements 1 and 3 were included in the next evaluation step.

Table 8
Interviewees' assessment of the two most preferred arrangements for Unipa village.

	Solution type	Feasibility	Negative impacts	Requirements	Risks
Arrangement 3	Tech	• Femtocells are technologically ready, available in the market and do not clash with the existing law and regulation • A similar system for battery performance prediction model is available in the market and has been used in some sites • Using the existing fibre optic is economically feasible	–	• Further assessment on the village's capacity need and growth potential • A termination point of fibre optic line near the location of the site	• Capital costs and operational costs for using femtocells in rural outdoor areas are unpredictable • If the location of the fibre optic line is not exactly on the settlement areas and there is mountain between the fibre optic line and the areas, using the fibre optic could be difficult (if not unfeasible)
	Org	• The village is among BAKTI's responsibility • BAKTI may not be fully an SRO as described in the solution due to its position as a government agency with many other responsibilities • involving the central and local authority as the organization solution is accommodated by existing regulations	• BAKTI would have a higher workload to manage and own more assets, need more technically skillful personnel and have a higher asset ownership risks	• Cooperation between BAKTI and an MNO to provide the service	–
	Reg	• Using USF for this village is allowed and accommodated in the existing regulation	–	–	–
Arrangement 1	Tech	• Femtocells are technologically ready, available in the market and do not clash with the existing law and regulation • A similar system for battery performance prediction model is available in the market and has been used in some sites • Using the existing fibre optic is economically feasible	–	• Further assessment on the village's capacity need and growth potential • A termination point of fibre optic line near the location of the site	• Capital costs and operational costs for using femtocells in rural outdoor areas are unpredictable • If the location of the fibre optic line is not exactly on the settlement areas and there is mountain between the fibre optic line and the areas, using the fibre optic could be difficult (if not unfeasible)
	Org	• Having an MNO to deploy the network for Unipa village with Option 1 is heavily influenced by the distance between the nearest MNO's network termination and the village	• Higher cost for deploying the site than if the site is deployed by BAKTI	• This village needs to be included in the MNO's coverage obligation	• The service price to users could be much higher than if the site is deployed by BAKTI
	Reg	• Different type of location (urban, rural and remote) might require different type of service that do not necessarily have the same quality • Reducing taxes to foster investments in rural areas is perceived sensible, but any policy that would negatively affect the national income would face opposition in the process of manifesting it into regulation	• Poor quality of service in many rural areas and the regulator cannot guard it • More explicit QoS gap between urban and rural areas	• QoS relaxation should be done only after assessing the actual condition of the site and applied only to the necessary sites • Amendments on the QoS regulations and taxes regulations • Change in the existing's government income-orientation • Combining the taxation policy with coverage obligation and appropriate punitive mechanism on the coverage obligation • The criteria that clarify which site eligible for QoS relaxation and the relaxation scheme that remains guarding the rights for rural users to receive an equal service quality • A careful tax reduction formulation	• The reduction of tax might not promote rural network development by MNOs as expected, especially if the tax is reduced first, before the MNO covers the rural areas

6.4.2. Stakeholder assessment of the selected arrangements

After the selection of the two preferred solution arrangements, we asked the interviewees to assess these solution arrangements on four pre-specified criteria: feasibility, negative impacts, requirements, and risks. These criteria are defined as follows:

- *Feasibility* describes whether or not an arrangement can be implemented and is sensible from the interviewee's point of view;
- *Negative impacts* refer to any direct adverse effect(s) that will *certainly* occur when the arrangement is implemented;
- *Requirements* list all prerequisites that have to be fulfilled for a feasible implementation;
- *Risks* are possible adverse effects that may or may not happen, depending on factors that are beyond our research project.

A summary of the interviewees' assessment of the preferred arrangements for Unipa village is presented in Table 8.

Based on the interviewees' combined assessments of the feasibility, negative impacts, requirements, and risks of both arrangements we categorized these criteria into High, Medium, and Low, as shown in Table 9. A description of these levels can be found in Appendix B. This categorization was approved by the interviewees.

An arrangement that has the highest feasibility and the lowest negative impacts, requirements, and risks can be considered the most suitable arrangement for the village. As seen from the overview in Table 9, arrangement 3 would be the preferred arrangement for Unipa village as, according to the interviewees, its feasibility is higher, and its negative impacts, requirements, and risks are lower than arrangement 1. Arrangement 3 for Unipa village includes TUCAN3G as the technological solution, an SRO to take the lead, and a Universal Service Fund (USF) as the regulatory solution. Arrangement 3 for Unipa village has medium-to-high feasibility and medium-to-low negative impacts, requirements, and risks. Therefore, the feasibility of implementation of the arrangement is considered high among the stakeholders that were interviewed.

6.5. Synthesis of demonstration case

In this section, we demonstrated the use of the DSS by applying it to the case of the unserved Indonesian village of Unipa. We reflect on the demonstration in the Discussion section.

7. Discussion

This article has two objectives. The first objective is to create an overview of the causes of the mobile coverage gap in rural locations and the different types of solutions to solve this gap, and how these solutions can be combined. The second objective is to develop an integrated method for governmental bodies to choose specific mobile communication solutions under specific circumstances, considering local characteristics and stakeholders' preferences. Both objectives address knowledge gaps in the academic literature. To reach the first objective, we developed, based upon an extensive literature review, an overview of the causes of the mobile coverage gap in rural locations and the different types of solutions to solve this gap, and how these solutions can be combined. To reach the second objective, we developed, based on our causes-solutions-combinations overview, a decision support scheme for selecting a suitable solution arrangement for solving the mobile coverage gap in a country or region. With the decision support scheme, several solution arrangements can be composed consisting of, first, a technological solution that fits the local context, second, an organizational solution that fits the technological solution and the local context, and, third, a regulatory solution that fits the technological and the organizational solution and the local context. The next step is having these solution arrangements evaluated by relevant stakeholders, to come to the optimal solution arrangement. We demonstrated the use of the DSS in the case of an unserved village in Indonesia.

Some limitations to our work need to be mentioned. The first limitation pertains to the fact that we based our overview of the causes of the mobile coverage gap in rural areas on a scientific literature review. However, a general notion is that published studies can suffer from selection bias such as against publishing null results. As a consequence, the importance of the variables identified in the literature can be either overstated or understated. Nevertheless, the causes of the mobile coverage gap in rural areas that we derived from our rigorous literature review offered a plausible perspective for taking technical, organizational, and institutional aspects into account to explore which solutions can address certain causes and how solutions can be selected and combined. However we do acknowledge that when our decision support system is used in practice, the local causes for the mobile coverage gap should be determined first to not preclude causes that are prominent in the local context but have not been covered in the academic literature. Hence, we encourage future cases to apply our decision support system for validation of its use but also for uncovering other, local causes that were not reported in the academic literature so far.

Another limitation of our research is the order in which the categories of solutions are applied in our case. We chose to start with a technological solution after which the organizational and regulatory solutions were considered in a funnelling way towards the final arrangement. However, alternative orders can be applied. E.g., if the starting point is a certain actor that wants to take the lead in solving the coverage gap, then the organizational solution comes first. Or, if the starting point is a new regulatory landscape and the question is which technological solutions and matching organizational solutions would fit with that. From the latter perspective, the decision support scheme could even be used to assess whether an existing regulatory framework still matches the currently available technological solutions – or whether it needs to be adapted.

The third limitation of our work has to do with consensus-seeking between stakeholders. Our demonstration case showed agreement among interviewees about the best solution arrangements in the evaluation step. Of course, this can be different in other local contexts or with the participation of a larger variety of stakeholders in the decision-making process. In that case, the decision support scheme can be used as a tool to channel the discussions to support the process towards a shared evaluation outcome.

The fourth limitation pertains to the evaluation criteria that we used: feasibility, negative impacts, requirements, and risks as other evaluation criteria can also be considered. Examples are whether the technical hardware for the solution arrangement is prone to theft or difficult to maintain and repair, and how expensive the mobile services would be for local users. Future research can investigate other evaluation criteria. The final limitation is in the selection of the interviewees, which was limited to six representatives from the Indonesian Ministry of Communications and Informatics and two representatives from two different

Table 9
Categorization of the feasibility, negative impacts, requirements, and risks of the arrangements for Unipa into high, medium and low.

Arr.	Feasibility			Consequences			Requirements			Risks		
	Tech	Org	Reg	Tech	Org	Reg	Tech	Org	Reg	Tech	Org	Reg
1	High	Medium	Low	Low	Medium	Medium	Low	Low	High	Medium	Low	Medium
3	High	High	High	Low	Medium	Low	Low	Low	Low	Medium	Low	Low

mobile network operators. Since we could not visit the village, the input from local people or NGO representatives could not be included whereas their viewpoints could have influenced the evaluation outcome. Setting up such an evaluation with a broader representation of stakeholders can be tested with new cases and is recommended for users of our decision support scheme.

This leads to the future research topic to investigate the role of the decision support scheme in practice. Do stakeholders indeed base their decisions on what comes out of this scheme, including an evaluation by local stakeholders? Or will the key stakeholders stay with their own preferences, and/or with the solution arrangement they are familiar with, which may not necessarily be the best solution arrangement available? Another recommendation for further research is the generalizability of the overview of causes and the decision support system to other infrastructures, such as electricity. The telecommunication case is a unique infrastructure case in the sense that this infrastructure with public interests/values has been liberalized and commercialized in many countries. But it is still a common infrastructure case in the sense that other infrastructures such as energy and transportation infrastructures also require high upfront investments with low returns on investment. Hence, in the past they were considered as infrastructures with public values that were guaranteed by public governance models. So the question is, which causes identified in this paper are also applicable to other infrastructures? And to what extent can the steps in the DSS also be useful for other infrastructure cases?

We developed a decision support scheme that can be used in any developing country as step-by-step guidance to develop solution arrangements for mobile coverage problems in rural areas. In the demonstration, we showed how the DSS can be used to arrive at a feasible arrangement for the selected case of Unipa village in Indonesia, including a stakeholder assessment.

For now, we consider the available and applicable solutions as listed in Tables 2, 3 and 4 up to date. Thus, a country's government can directly use these tables to support its effort to advance mobile coverage in rural areas. However, for future efforts to advance mobile coverage in rural areas, we suggest that the literature review for the inventory of available technological solutions is revisited to fit with the state of the art in technological innovation in mobile networks and services.

8. Conclusion

As mobile telecommunications services play a crucial role in developing countries, a comprehensive perspective on finding solutions for closing the mobile coverage gap is needed. In a literature review to explore potential solutions we found that only partial solutions such as in technologies or regulations are covered separately. Therefore, we developed an integral decision support scheme for decision makers to go beyond these partial solutions and to involve stakeholders to develop and prioritize potential solution arrangements. We demonstrate the decision support scheme by means of a case in the rural Indonesian Unipa village.

Our scientific contribution is demonstrating how partial solutions that are covered in the academic literature separately can be combined to develop an integral solution arrangement that aligns with the local context and causes of mobile coverage gaps in rural areas in developing countries. In addition, we include the important role of stakeholders in the development and assessment of potential solution arrangements as they are the key decision makers and contributors to enter the phase of implementation of the chosen solution arrangement. Hence, we complement the predominantly economic and regulatory literature on (gaps in) mobile communications networks with the societal and business aspects.

Our societal contribution is the design of an integrated decision support system for guiding the process of choosing a specific mobile communication solution that can be used by researchers, governments, or mobile network operators. The decision support system offers a step-by-step, interactive, multi-stakeholder approach for exploring and formulating solutions for the mobile coverage problem in rural areas, local characteristics and stakeholders' preferences into account. As such, our decision support system by its interactive nature contributes to closing the mobile coverage gap by crossing the boundaries between technological, organizational, and economic perspectives and invites stakeholders to take part in a decision-making process to combine their capacities and resources. We consider such an interactive, dynamic multi-stakeholder process essential to address and overcome the barriers towards the much-needed access to mobile telecommunications services in rural areas in developing countries.

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CRediT authorship contribution statement

Vannesya Harahap: Conceptualization, Investigation, Methodology, Validation, Writing – original draft. **Linda M. Kamp:** Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jolien Ubacht:** Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors have no competing interests.

Data availability

Data will be made available on request.

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Appendix A

This table overview presents the sources that were used in the literature review for creating:

- the overview of the key issues for the lack of mobile coverage in developing countries (see Section 3) and
- the inventory of available solutions to remedy this lack of mobile coverage in developing countries (see Section 4).

The full references can be found in the reference list. See Section 2 for the search and selection process of the literature review.

Table A.1
Sources used in the literature review.

Ref.nr.	Author(s)	Year	Publication	Problem analysis	Solutions
Anand et al. (2012)	Anand, A, Pejovic, V, Johnson, D.L., Belding, E.M.	2012	VillageCell: Cost effective cellular connectivity in rural areas		X
Arakpogun et al. (2017)	Arakpogun, E. O., Wanjiru, R., & Whalley, J.	2017	Impediments to the implementation of universal service funds in Africa – A cross-country comparative analysis	X	X
Barela et al. (2016)	Barela, M.C., Blanco, M.S., Martinz, P., Purisima, M.C, Heimerl, K., Podolsky, M., Brewer, E., Festin, C.A.	2016	Towards Building a Community Cellular Network in the Philippines: Initial Site Survey Observations		X
Berg and Hamilton (2002)	Berg, S. V, & Hamilton, J.	2002	Institutions and Telecommunications Performance in Africa: Stability, Governance and Incentives	X	
Bhuiyan (2004)	Bhuiyan, A. J. M. S. A.	2004	Universal Access in Developing Countries: A Particular Focus on Bangladesh	X	
Borst et al. (2010)	Borst, S., Gupta, V., Walid, A.	2010	Distributed caching algorithms for content distribution networks		X
Irwin and Brook (2003)	Irwin, T.C. & Brook, P. J.	2003	Private infrastructure and the poor: Increasing access	X	
Chavula (2013)	Chavula, H. K.	2013	Telecommunications development and economic growth in Africa	X	
Chiaraviglio et al. (2019)	Chiaraviglio, L., Amorosi, L., Blefari-Melazzi, N., Dell'olmo, P., Lo Mastro, A., Natalino, C., & Monti, P	2019	Minimum Cost Design of Cellular Networks in Rural Areas with UAVs, Optical Rings, Solar Panels, and Batteries		X
Chiaraviglio et al. (2017a)	Chiaraviglio, L., Blefari-Melazzi, N., Liu, W., Gutierrez, J. A., Van De Beek, J., Birke, R., Chen, L., Idzikowski, F., Kilper, D., Monti, J. P., & Wu, J.	2017	5G in rural and low-income areas: Are we ready?		X
Chiaraviglio et al. (2017b)	Chiaraviglio, L., Blefari-Melazzi, N., Liu, W., Gutierrez, J. A., Van De Beek, J., Birke, R., Chen, L., Idzikowski, F., Kilper, D., Monti, P., Bagula, A., & Wu, J.	2017	Bringing 5G into Rural and Low-Income Areas: Is It Feasible?		X
Chiha et al. (2020)	Chiha, A., Van der Wee, M., Colle, D., & Verbrugge, S.	2020	Techno-economic viability of integrating satellite communication in 4G networks to bridge the broadband digital divide.		X
Cricelli et al. (2011)	Cricelli, L., Grimaldi, M., & Levialdi, N.G.	2011	The competition among mobile network operators in the telecommunication supply chain.		X
Cruz and Touchard (2018)	Cruz, G., & Touchard, G.	2018	Enabling Rural Coverage Regulatory and policy recommendations to foster mobile broadband coverage in developing countries	X	X
Fan et al. (2016)	Fan, X., Wang, F., & Liu, J.	2016	Boosting service availability for base stations of cellular networks by event-driven battery profiling		X
Galperin and Bar (2007)	Galperin, H., & Bar, F.	2007	The Microtelco Opportunity: Evidence from Latin America	X	
Gieling (2018)	Gieling, J.	2018	A place for life or a place to live. Rethinking village attachment, volunteering and liveability in Dutch rural area		X
Grampín et al., 2007	Grampín, E., Baliosian, J., Visca, J., Giachino, M., & Vidal, L.	2007	Wireless network architecture for digital inclusion in rural environments		X
Galperin and Bar (2007)	Gutierrez, L. H., & Berg, S.	2000	Telecommunications liberalization and regulatory governance: Lessons from Latin America	X	
Heimerl et al. (2013)	Heimerl, K., Hasan, S., Ali, K., Brewer, E., & Parikh, T.	2013	Local, Sustainable, Small-Scale Cellular Networks.	X	X
Hudson (2006)	Hudson, H. E.	2006	From rural village to global village: Telecommunications for development in the information age	X	
Ilcev and Singh (2004)	Ilcev, S. D., & Singh, A.	2004	Development of stratospheric Communication Platforms (SCP) for rural applications		X
ITU (1999)	ITU	1999	World Telecommunication Development Report 1999: Mobile Cellular	X	
Jha and Saha (2016)	Jha, A., & Saha, D.	2016	Techno-economic assessment of the potential for LTE based 4G mobile services in rural India		
Kabir et al. (2018)	Kabir, A., Kitindi, E. J., Ul Abidin Jaffri, Z., Rehman, G., Ubaid, F. Bin, & Iqbal, M. S.	2018	Economical and sustainable power solution for remote cellular network sites through renewable energy		X
Khaturia et al. (2020)	Khaturia, M., Jha, P., & Karandikar, A.	2020	Connecting the Unconnected: towards Frugal 5G Network Architecture and Standardization	X	
Kiiski and Hämmäinen (2004)	Kiiski, A., & Hämmäinen, H.	2004	Mobile Virtual Network Operators: Case Finland		X
Lun et al. (2019)	Lun, J., Frenger, P., Furuskar, A., & Trojer, E.	2019	5G new radio for rural broadband: How to achieve long-range coverage on the 3.5 GHz band.		X
Martínez-Fernández et al. (2016)	Martínez-Fernández, A., Vidal, J., Simó-Reigadas, J., Prieto-Egido, I., Agustín, A., Paco, J., & Rendón, Á.	2016	The TUCAN3G project: Wireless technologies for isolated rural communities in developing countries based on 3G small cell deployments.		X
McDowell and Lee (2003)	McDowell, S. D., & Lee, J.	2003	India's experiments in mobile licensing		X
Minges (1998)	Minges, M.	1998	African telecoms: Private sector to the rescue?	X	
Montenegro and Araral (2020)	Montenegro, L. O., & Araral, E.	2020	Can competition-enhancing regulation bridge the quality divide in Internet provision?	X	X

(continued on next page)

Table A.1 (*continued*)

Ref.nr.	Author(s)	Year	Publication	Problem analysis	Solutions
Palazzi et al. (2011)	Palazzi, C. E., Bujari, A., Bonetta, S., Marfia, G., Roccetti, M., & Amoroso, A.	2011	MDTN: Mobile delay/disruption tolerant network		X
Philip et al. (2017)	Philip, L., Cottrill, C., Farrington, J., Williams, F., & Ashmore, F.	2017	The digital divide: Patterns, policy and scenarios for connecting the 'final few' in rural communities across Great Britain		X
Prieger (2013)	Prieger, J.E.	2013	The broadband digital divide and the economic benefits of mobile broadband for rural areas	X	
Prieto Egido et al. (2020)	Prieto Egido, I., Aragon Valladares, J., Muñoz Medina, O., Cordoba Bernuy, C., Simo Reigadas, J., Auccapuri Quispetupa, D., Bravo Fernández, A., & Martinez Fernandez, A.	2020	Small rural operators techno-economic analysis to bring mobile services to isolated communities: The case of Peru Amazon rainforest	X	X
Rendon Schneir and Xiong (2016)	Rendon Schneir, J., & Xiong, Y.	2016	A cost study of fixed broadband access networks for rural areas	X	
Rey-Moreno et al. (2011)	Rey-Moreno, C., Bebea-Gonzalez, I., Foche-Perez, I., Quispe-Tacas, R., Liñán-Benitez, L., & Simo-Reigadas, J.	2011	A Telemedicine WiFi Network Optimized for Long Distances in the Amazonian Jungle of Peru		X
Roberts et al. (2017)	Roberts, E., Beel, D., Philip, L., & Townsend, L.	2017	Rural resilience in a digital society: Editorial	X	
Salemink and Strijker (2018)	Salemink, K., & Strijker, D.	2018	The participation society and its inability to correct the failure of market players to deliver adequate service levels in rural areas.	X	X
Simó-Reigadas et al. (2019)	Simo-Reigadas, J., Municio, E., Morgado, E., Castro, E. M., Martinez, A., Solorzano, L. F., & Prieto-Egido, I.	2019	Sharing low-cost wireless infrastructures with telecommunications operators to bring 3G services to rural communities.		X
Son et al. (2019)	Son, P. H., Son, L. H., Jha, S., Kumar, R., & Chatterjee, J. M.	2019	Governing mobile Virtual Network Operators in developing countries.		X
Sridhar and Prasad (2011)	Sridhar, V., & Prasad, R.	2011	Towards a new policy framework for spectrum management in India.		X
Surana et al. (2008)	Surana, S., Patra, R., Nedevschi, S., Ramos, M., Subramanian, L., Ben-David, Y., & Brewer, E.	2008	Beyond Pilots: Keeping Rural Wireless Networks Alive	X	
Sutherland (2014)	Sutherland, E.	2014	Mobile telecommunications in Africa: Issues for business, government & society	X	
Thakur et al. (2017a)	Thakur, R., Mishra, S., & Murthy, C. S. R.	2017	An energy and cost aware framework for cell selection and energy cooperation in rural and remote femtocell networks.		X
Thakur et al. (2017b)	Thakur, R., Narayan Swain, S., & Siva Ram Murthy, C.	2017	Cell selection and resource allocation for sleep mode enabled femtocells with backhaul link constraint.		X
Touchard (2017)	Touchard, G.	2017	Connected Society Unlocking Rural Coverage: Enablers for commercially sustainable mobile network expansion	X	X
Townsend et al. (2013)	Townsend, L., Sathiaseelan, A., Fairhurst, G., & Wallace, C.	2013	Enhanced broadband access as a solution to the social and economic problems of the rural digital divide	X	
Trendov et al. (2018)	Trendov, N., Varas, S., & Zeng, M.	2018	Digital technologies in agriculture and rural areas: Status report	X	
Tyler et al. (1995)	Tyler, M., Letwin, W., & Roe, C.	1995	Universal service and innovation in telecommunication services: Fostering linked goals through regulatory policy	X	
Valletti (2001)	Valletti, T.M.	2001	Spectrum trading		X
Wade (2015)	Wade, L.	2015	Where Cellular Networks Don't Exist, People Are Building Their Own		X
Wang et al. (2017)	Wang, S., Zhang, X., Zhang, Y., Wang, L., Yang, J., & Wang, W.	2017	A Survey on Mobile Edge Networks: Convergence of Computing, Caching and Communications		X
Wanjiku (2014)	Wanjiku, R.	2014	Kenya starts Universal Service Fund implementation	X	
Whitehead et al. (2011)	Whitehead, M., Phillips, T., Page, M., Molina, M., & Wood, C.	2011	European Mobile Industry Observatory 2011 Driving Economic and Social Development through Mobile Broadband	X	
Wright (1995)	Wright, D.	1995	Reaching out to remote and rural areas: Mobile satellite services and the role of Inmarsat	X	X

Appendix B

Table B.1
Categorization of the feasibility, negative impacts, requirements, and risks of the arrangement.

	Level	Technology	Organization	Regulatory
Feasibility	High	Is commercially available, has been implemented in Indonesia, does not clash with the existing regulation and is technically implementable	Does not clash with the existing regulation and has no uncertain factor	Allowed by the existing regulations and business process
	Medium	Is commercially available but technically unimplementable or clashes with the existing regulation	Need a feasible adjustment to the existing regulation	Requires a feasible change in the existing regulation

(*continued on next page*)

Table B.1 (*continued*)

	Level	Technology	Organization	Regulatory
	Low	Is commercially not available and clashes with the existing regulation	Need an unfeasible adjustment to the existing regulation	Requires a nearly unfeasible change in the existing regulation
Negative impacts	High	Unsatisfying network service, high deployment cost, and complicated operation	High deployment cost and complicated operation	Worse telecommunication sector condition than if without the solution
	Medium	Unsatisfying network service, high deployment cost or complicated operation	High deployment cost or complicated operation	Service quality gap
	Low	No identified negative impacts	No identified negative impacts	No identified negative impacts
Requirements	High	Adjustment on the existing regulation, field study, adjustment on the existing industry (such as major adding new skill for the existing network engineers)	An unfeasible adjustment on the existing business process and policy	An unfeasible adjustment on the existing system and regulation
	Medium	Field study and adjustment on the existing regulation or adjustment on the existing industry (such as major adding new skill for the existing network engineers)	A feasible adjustment on the existing business process and policy	A feasible adjustment on the existing system and regulation
	Low	Next steps that can be performed directly, such as field study and the network planning	Next steps that can be performed directly, such as cooperating with other organization, adjusting the coverage obligation	No identified requirements
Risks	High	The risks can detoriate the condition (such as residents' resentment and disturbance to locals)	The risks can detoriate the condition (such as residents' resentment and disturbance to locals)	The risks can detoriate the condition (such as residents' resentment and disturbance to locals)
	Medium	The risks that could make the solution ineffective (such as unpredictable cost and/or technical obstacle)	The risks that could make the solution ineffective (such as unpredictable cost and/or technical obstacle)	The risks that could make the solution ineffective (such as unpredictable cost and/or technical obstacle)
	Low	No identified risk or the risk is acceptable	No identified risk or the risk is acceptable	No identified risk or the risk is acceptable

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