Hidden Gateways to Digital Space - the spatial distribution of Wi-Fi networks in the context of demographic structure in rural areas

Krzysztof Janc
e-mail: krzysztof.janc@uwr.edu.pl
Department of Spatial Management, Institute of Geography and Regional Development, Faculty of Earth Sciences and Environmental Management, University of Wroclaw
ORCID:0000-0002-1666-2848

Marcin Mazur,
e-mail: m.mazur@twarda.pan.pl
Polish Academy of Sciences, Institute of Geography and Spatial Organization, Twarda 51/55, 00-818, Warszawa, Poland

Damian Mazurek,
e-mail: d.mazurek@twarda.pan.pl
Polish Academy of Sciences, Institute of Geography and Spatial Organization, Twarda 51/55, 00-818, Warszawa, Poland
ORCID: 0000-0003-1056-1752

Wojciech Jurkowski
e-mail: wojciech.jurkowski@uwr.edu.pl
Department of Spatial Management, Institute of Geography and Regional Development, Faculty of Earth Sciences and Environmental Management, University of Wroclaw
ORCID: 0000-0002-8926-3004

Marcin Wójcik,
e-mail: marcin.wojcik@geo.uni.lodz.pl
University of Łódź, Department of Regional and Social Geography, Kopcińskiego 31, 90-131, Łódź, Poland
ORCID: 0000-0002-5236-5381

Abstract:
Despite being seemingly invisible, digital space exerts a profound influence on society and economy. Similarly, the vast number of digital devices we use to access it – often invisible themselves – act as gateways to this realm. Identifying and mapping these hidden gateways to digital space can reveal the complexity of human activities functioning across real and digital spaces, and in between them. The conducted study aimed to identify spatial patterns in the distribution of Wi-Fi networks at a local scale in the context of demographic structure. It analysed the distribution of public and private Wi-Fi networks, which can be treated as hidden gateways to digital space. The spatial scope of this research encompassed rural areas of five Polish communes, chosen as representatives of different categories within the adopted typology. The main conclusion is that the spatial distribution of Wi-Fi networks is closely linked to the spatial distribution of younger age groups. This finding highlights issues related to the digital divide, particularly concerning varying digital competencies and needs. Additionally, it turns out that the strength of the relationship between people and Wi-Fi networks does not depend on the type of area or its specific characteristics.

Keywords: Wi-Fi networks, digital space, hidden gateways, rural areas, wardriving

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1. Introduction

Society and economy are progressively becoming more reliant on information technologies, whether urban or rural areas (Streitz, 2018). This trend is driven by the internet, which must now be acknowledged as a pivotal catalyst for socio-economic development (Magnusson, Hermelin, 2019; Tranos, 2013). Notably, the accessibility to and proficiency in utilizing the internet have evolved into daily necessities, regardless of the purpose - whether work or entertainment. The availability of internet access is increasingly recognized as a fundamental human right (El Massah, Mohieldin, 2020), thereby positioning it as an essential utility tantamount to access to clean water and electricity. The ubiquity of applications and the wide range of facilities associated with using the internet have fostered a need for constant, unlimited access to fast and reliable internet connections, free from geographical constraints.

The necessity of staying constantly connected becomes even more obvious when we consider the number of individuals using the internet worldwide. There were 5.4 billion internet users in 2023, accounting for 67% of the world's population (ITU, 2024).As a result of their use of the Internet on different digital devices, a digital space is created. It consists of data generated by people in different contexts, situations, and locations, but always in the presence of digital technologies. Digital space increasingly influences and intertwines with real space. Actions taken in one of these spaces have consequences in the other (Zook, Graham, 2007; Ash et al., 2018), leading to the creation of hybrid space (Kellerman, 2020).

The overlapping of these two spaces - the need to function between them or to be "immersed" in two of them at the same time - contributes to the emergence of spaces at the intersection. This space is constantly shaped as a result of the relationship between real/physical space and mental/imagined space. It can be recognized as a digital space; fluid and interwoven with the actions and experiences of everyday life (Soja, 2008; Blake, 2002). Regarding this, a triad appears: real space, digital space, and the third space, which can be described as "...a blended space that possesses characteristics of the other two spaces. It is in this space where the user can manage his life in the two spaces..." (Kosari, Amoori, 2018: 166). An essential element enabling the experience and creation of the third space, allow us to move between spaces is hidden gateways to the digital space. Nowadays, the role of hidden gateways is greatly played by Wi-Fi networks, which represent an expression of the increasing pervasiveness of internet-based technologies and the broadening of their influence (Blank, Dutton, 2014). Wi-Fi networks are essential as they provide the infrastructure for so-called wireless access. Wireless access has emerged as a critical part of the Internet's functionality, meeting the needs of users in both public and private spaces; as a result, Wi-Fi signals are being integrated into everyday life (Perng, 2015). This is particularly evident with the advent of smartphones, other portable devices and the mobile internet, which represent a milestone in the development of the internet by enabling connectivity from nearly anywhere.

However, due to spatial differences in access and internet performance in specific areas, some communities (especially rural ones) are excluded from full participation in the modern information society (Salemnik et al., 2017; Birnbaum et al., 2021). This exclusion also applies to access to Wi-Fi networks, which poses a significant research problem in the context of spatial analysis. This problem involves identifying the spatial aspects not only of internet access itself but also of the distribution of Wi-Fi networks – their relationships with population, user characteristics, and consequently, the emergence of spatial divisions. Despite the "immateriality" of most divisions associated with internet use, the created digital space, it should be assumed that they are "grounded" in the physical characteristics of space, such as functional types of space, spatial development, and variability of social and demographic space.

The main purpose of this study is to identify spatial patterns in the distribution of Wi-Fi networks at a local scale in the context of demographic structure. The aim is pursued by analysing the spatial distribution of public and private Wi-Fi networks in rural areas, which can be identified as hidden gateways to the digital space. A key element of the analysis is to explore the relationships between Wi-Fi network distribution and the demographic characteristics of residents, as these factors are typically identified as significant determinants of digital technology usage at global, national, or regional levels. The research was conducted in five rural-type communes in Poland, encompassing several villages. This approach enabled the consideration of the diverse spaces studied and provided a comprehensive presentation of the local dimension, considering the various characteristics of spatial structure. Based on the key assumptions of this study, the research question (RQ) was formulated as follows: does the distribution of Wi-Fi networks correlate with the distribution of different age groups? The answer to this question is pursued not only by figuring out statistical dependencies but also by creating a typology of spatial units.

In the context of the above-mentioned issue, an important research gap should be acknowledged. Essentially, the identification of hidden gateways requires determining the spatial distribution in Wi-Fi networks and explaining the reasons for this pattern. This type of approach is known from urban research (e.g., Torrens, 2008; Konomi et al., 2019), which involves scanning Wi-Fi networks to obtain a pattern of the diversity of their distribution. What is lacking are studies that comprehensively characterize the spatial dimension of Wi-Fi networks in rural areas. Additionally, it should be noted that while the literature on public Wi-Fi hotspots is fairly well represented in research on wireless internet access (e.g., Kim, 2018; Tang et al., 2019; Wang et al., 2016), studies focusing on local (particularly beyond urban areas) and comprehensive Wi-Fi access (taking into account private networks) are absent in spatial research literature. Importantly, research on the use of open/municipal Wi-Fi in urban contexts clearly shows that demographic factors such as age and generational membership influence their usage (McConnell, Straubhaar, 2015).

2. Theoretical background – analysing space in the age of wireless access.

2.1. Between two spaces – hidden gateways

The current development of information technology contributes to the emergence of digital space, which creates numerous connections and new forms of links between existing spatial structures and new forms of social activity online (Zook, Graham, 2007; Ratti, Claudel, 2016; Boos, 2017). Identifying these intangible and invisible manifestations of contemporary life in real space is a significant challenge for spatial research. This applies not only to the transfer of data and its consequences, but also to the fundamentals of creating and operating in digital space, including the devices that make it possible.

Consequently, in the spatial context, we must face the challenge of redefining our research approaches as our understanding of space is transformed into new dimensions (Harvey, 2012). Since the 1980s and 1990s, there has been intense reflection on the complexities of social space (Soja, 1989; Merriman et al., 2012; Massey, 2013). However, the development, expansion, and increasing complexity of digital space have led to a growing awareness that this has myriad social consequences (Aoyama, Sheppard, 2003). The interactions between real space and digital space require researcher to rethink issues related to the functioning of space itself, as well as the space emerging between them. This, in turn, concerns both material and social issues and the shaping of spatial reality, sometimes referred to as 'blended space' (Kosari, Amoori, 2018) or more specifically as 'socio-cyber-physical systems' (Metta et al., 2022).

Real space, with its physical objects, infrastructure, and material manifestations of human activity, is simultaneously 'saturated' with digital activity. We live in an environment where a vast number of digital devices create overlapping fields of access to digital space, enabling us to experience it. Importantly, as noted by Ylipulli et al. (2014), users within a given technology society adapt and integrate it into their daily practices. As a result, technology will shape both the user's environment and the user themselves. Digital space is seemingly invisible, yet it exerts a profound influence on our lives. Similarly, the devices we use to access it – often invisible themselves – act as gateways to this realm. In this context, identifying and mapping these hidden, invisible gateways to the digital world can reveal the complexity of human activities, functioning across real and digital spaces, and in between them (Fig. 1). Recognizing this specific system of interaction is one way of evaluating human functioning within the living environment and connecting it with other aspects. This can be metaphorically described as fields and channels leading to invisible gateways behind which lies the other set of spatial phenomena - digital space.

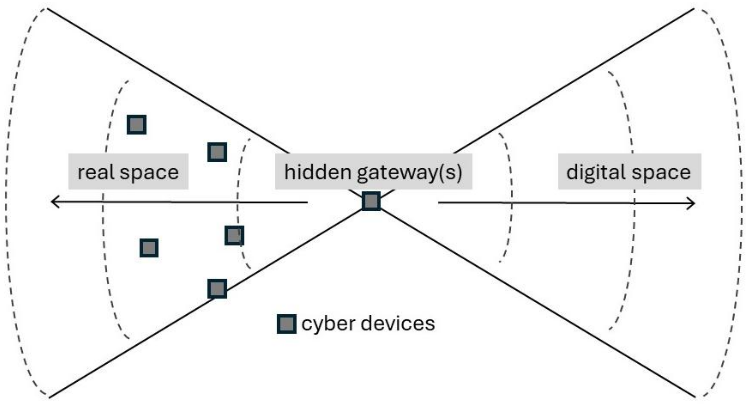

Fig. 1. Wi-Fi networks as hidden gateways to digital space.
Source: own's elaboration

The conceptualisation presented above of the relationship between two spaces and the role of cyber devices as hidden gateways needs to be examined from the point of view of how they operate in present-day conditions. Emerging questions about the nature of spaces formed because of using digital technologies - their intertwining in our everyday lives (Forlano, 2009). A prerequisite for understanding these issues is the recognition of the characteristics, conditions, and spatial distribution of these digital devices.

2.2. Wi-Fi networks – hidden gate to cyberspace

The need for instant access to the internet is influenced by the necessity of accessing information and services from any location. From a household perspective, the internet is utilized in every room and immediate surroundings, primarily through Wi-Fi. In addition, the proliferation of connected devices, including home appliances, peripherals and sensors, requires them to be connected to a single wireless network. The transition, from stationary use of a single device to mobile use of multiple devices, exemplifies the realization of smart development (e.g., Albino et al., 2015; Nam, Pardo, 2011; Naldi et al., 2015; Wolski, Wojcik, 2019; Komorowski, Stanny, 2020). This reliance depends on internet access in various aspects. The interconnection of Internet of Things (IoT) devices such as smartphones, tablets, laptops, desktops, smart TVs, video cameras, monitors, printers and other consumer electronic devices enables a wide range of applications to meet the needs of users wherever they are. Consequently, a complex space emerges from the interplay of people, institutions, technology, the built environment, and physical infrastructure (Chourabi et al., 2012). Thomas et al. (2021) report that by the end of the second decade of the 21st century, broadband-connected households in the US had an average of about nine Wi-Fi-connected devices. This highlights how reliant we are on wireless internet. With the development of the IoT, the combination of devices that we use daily to meet our needs - an 'environment' that we can describe as 'smart' - is being created. Thus, spaces of activity such as rooms, houses, vehicles, cities, and villages are becoming 'smart spaces' (Streitz, 2019) and as in all spaces, there are visible divisions within them.

In the case of wireless internet, there are currently two wireless data interfaces for connecting a mobile device to the internet: wireless local area networks (Wi-Fi) and cellular mobile data networks. As noted by Pahlavan and Krishnamurthy (2021), Wi-Fi is the preferred choice for smartphone users because it can provide higher data rates and more reliable indoor connections at a lower cost; users typically resort to cellular networks as a secondary choice. Wireless internet (Wi-Fi), also known as Wireless Fidelity, is based on the IEEE 802.11 family of standards, the basic version of which was published in 1997. It is evident that wireless data is making steady progress, particularly in terms of traffic growth. However, significantly, the emergence and proliferation of mobile technology known as '5G' and its unlimited mobile data plans do not indicate a decline in the importance of Wi-Fi (Oughton et al., 2021).

In this study, we assume that materials digital devices in the form of Wi-Fi routers serve as the foundation for the operation of intangible Wi-Fi networks. Therefore, it is worth emphasizing that the mapping of Wi-Fi networks should always be considered in relation to their embeddedness in physical space (Kim, 2018).It is therefore important to refer to the functions and structure of space, as they both determine human spatial behaviour and are its product - the effect of activities related to, for example, the creation of the material framework of digital space. When addressing the spatial dimensions of Wi-Fi, the focus is typically on public (open) access within the smart city concept (Kamienski et al., 2020). It's important to note that public Wi-Fi offers new opportunities to engage both residents and visitors (e.g. tourists) in urban activities. Public Wi-Fi access allows people to benefit from the many amenities offered by the smart city (Louw, Von Solms, 2019). Research in Australia has shown that the promotion of tourism and digital inclusion are the two main reasons for providing public Wi-Fi (McShane, Grechyn, 2019). Extending this perspective to rural areas and it's clear that Wi-Fi access performs a similar function. Additionally, it contributes to enhancing internet-based solutions, thereby enabling better monitoring and management of farms and agricultural activities in general (Wolfert et al., 2017).However, as emphasized by Morris et al. (2022), the geographical location still significantly impacts access to reliable digital connectivity. Consequently, despite investments, rural and remote areas face disadvantages.

The identified inequalities in internet access are analyzed across various spatial scales, including disparities between regions and countries, as well as between rural and urban areas (e.g., Gorman, Malecki, 2000; Grubesic, O'Kelly, 2002; Whitacre, Mills, 2007; Stephens, Poorthuis, 2015).It should be noted that it is not so much access itself that is important, but also how the internet is used and by whom (Brandtzæg et al. 2011). Issues of digital literacy (Hargittai, 2002) and the benefits gained from using the internet (van Deursen, Helsper, 2015) have become important elements in analysing issues related to the development of specific areas. Internet users began to use multiple devices to connect to the internet, often 'on the move' and from multiple locations (Blank and Dutton, 2014; Lee et al., 2015). Hence, it is important to consider that uneven internet access and its utilization are influenced not only by location (e.g., urban/rural), but also by social, cultural, and economic factors. All these factors are intertwined with the demographic structure, particularly the age of residents, which itself is deemed a significant determinant shaping the extent and scope of the digital divide (Haight et al., 2016; Elena-Bucea et al., 2021).

It should be noted that prior research on the spatial distribution of Wi-Fi networks at the local scale has consistently confirmed a relationship between the Wi-Fi networks density and areas with values of income, residents' educational attainment, lifestyle, and other socioeconomic characteristics of urban residents (Grubesic, Murray, 2004; Fuentes-Bautista, Inagaki, 2006; Torrens, 2008; Driskell, Wang, 2009). Similar to this, the utilisation of public Wi-Fi networks is significantly influenced by educational capital and techno-capital (i.e., confidence with typical computer tasks) (McConnell, Straubhaar, 2015).

3. Methodology

In this study, the authors have employed methods encompassing a broad understanding of spatial analysis and field research (inventory). The research procedure in this study can be divided into two main stages (Fig. 2).

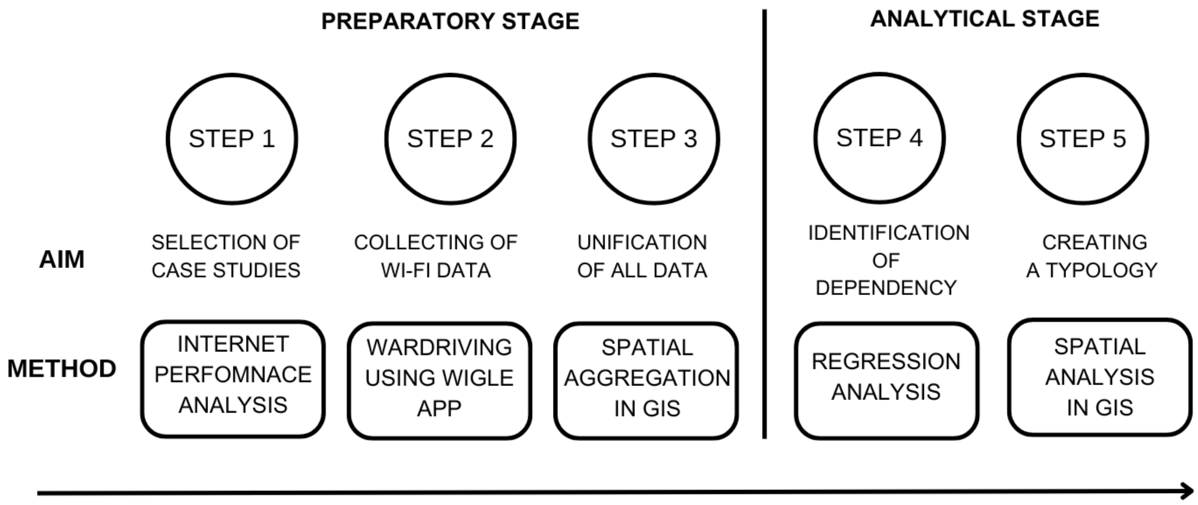

Fig. 2The scheme of the research procedure for analysing the study results.
Source: own's elaboration

3.1. Preparatory stage

The first step in the research process was to select case studies. The reference point for the selection process was a typology of communes, which was conducted based on the level of current internet performance and its dynamic of change[1].As a result, 1814 rural communes in Poland were classified into 5 types, each characterized by distinct features in the examined aspects. To ensure a high level of representativeness of case studies, the selection of case studies was carried out in a targeted random manner (Frankfort-Nachmias et al., 2014), with a case study representing each type of commune. Ultimately, 5 communes were chosen for the study: Bierutów, Kuślin, Szadek, Orońsko, and Suwałki (Fig. 3), encompassing 117 villages and 2 towns. These communes represented areas with diverse local settlement structures, varying historical backgrounds, and differing local economic structures. They included both rural areas with suburban characteristics (e.g., Suwałki commune, where the commune seat is in a neighboring town) and those distant from larger cities (e.g., Kuślin commune).

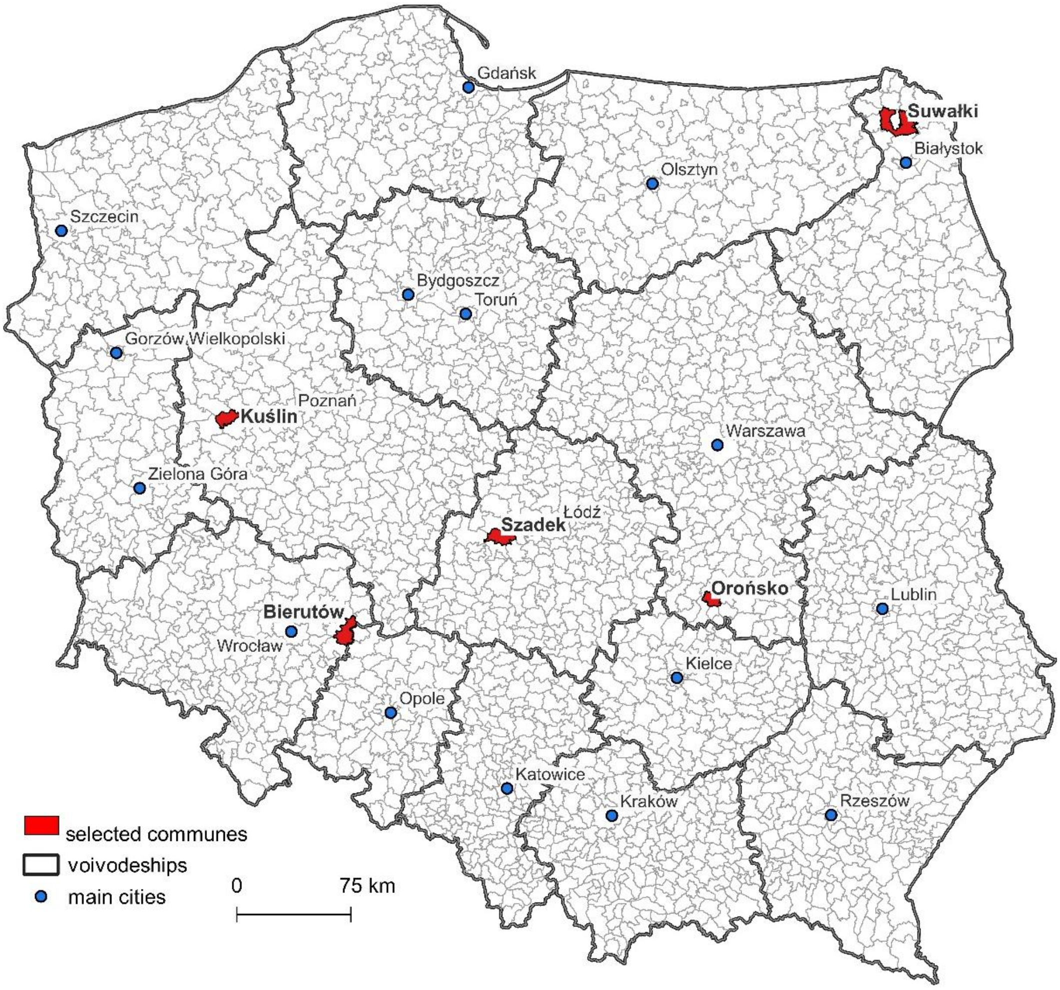

Fig. 3. Localization of selected communes (case studies) for analysing in Poland
Source: own's elaboration

[1]The analysis of the level of internet performance in each commune was based on data provided by Ookla. These data, which also allow for dynamic research, are currently the only data available at the level of local administrative units(Janc et al., 2022).

Fig. 4. Case studies areas.
Source: own's elaboration

The second stage of research procedure involved collecting data from all locations within the selected five communes. The data was collected manually by scanning networks using a passenger car in all locations of individual communes, following the principles of wardriving (see Tsui et al., 2010). Wardriving can be defined as "moving around (not necessarily in an automobile) a designated geographical area and scanning to enumerate wireless access points and their operational state in real time" (Etta et al., 2022, p. 2).

The data was obtained using smartphones running on the Android operating system with the WiGLE WiFi application. WiGLE WiFi allows scanning of Wi-Fi networks, as well as

Bluetooth and GSM base stations. Due to the characteristics of the Wi-Fi signal detection tools, the vehicle was driven at a slow speed, typically up to 20 km/h. A smartphone with the WiGLEWiFi application and Bluetooth turned on was placed near the front windshield of the car. Each route was scanned multiple times, considering various factors such as dense buildings or the need to move faster than 20 km/h. The time interval between consecutive scans was configured in the application as follows: every 10 seconds when the vehicle was stationary, every 5 seconds when the vehicle was moving at speeds up to 8 km/h, and every 1 second when the vehicle was moving at speeds greater than 8 km/h.The research was conducted during June and July 2022, on weekdays, and it spanned from one to three days in each commune, depending on the level of settlement network dispersion in commune.

The objective of the field research was to cover all accessible locations within the commune that a "normal" user would typically encounter. As a result, closed residential complexes such as gated communities, industrial areas with restricted access, and military facilities were excluded from the study. It is worth noting that in rural areas, it was sometimes impossible to approach or closely examine dwellings and buildings due to fenced properties. These limitations could potentially impact the analysis results, as Tang et al. (2019) indicated that the effective signal area for Wi-Fi networks typically ranges from about 100 to 300 meters. However, it is important to emphasize that closed facilities constituted only a small percentage of the overall study area. Moreover, a significant portion of the network signals were captured without the need to enter private areas (scanning at the entrance gate). Therefore, it can be concluded that closed facilities were represented to a lesser extent rather than being completely ignored in the research.

The characteristics of the operation WiGLE Wi-Fi application is that it identifies each device when it is detected in each location and consequently records it in the database, the location being the location of the scanning device. Consequently, multiple measurements (and therefore locations) must be averaged to obtain a single spatial location for a single Wi-Fi network. This was done by determining the centres of gravity for those networks whose signal was recorded from multiple scanning device locations. The Wi-Fi network was identified using the device's unique ID (MAC address).In total, the scanning yielded a dataset of 38,863 records, and after removing duplicates, 7,339 unique MAC addresses remained, representing identified Wi-Fi networks along with their locations.

In the next step of the research procedure, Wi-Fi data was unified with other data types using spatial aggregation. The optimal spatial layout for the analysis was a model consisting of a network of adjacent hexagons with an area of 25 ha. The location of the Wi-Fi network identification point in hexagons was described by the index h.The Wi-Fi network location data had a discrete nature. Their spatial attribute was the specific geographic coordinates of the identification point of a given network. Therefore, they could be aggregated within hexagons. The number of networks identified in each hexagon was denoted by the symbol I_h.

Demographic data comes from the census (2021 Population Census) and allows for determining the population size and the share of residents in the following three age groups ($Dem_{d,r}$): up to 14. Years old ($d = 1$), between 15. a 64. Years old ($d = 2$) and 65 years old or older ($d = 3$). However, it should be emphasized that this data, at the smallest possible spatial resolution, is aggregated into reference fields with a GRID structure, with a grid cell size of 100 hectares, where $r$represents the index of the grid.

The structure of the population data differs from the 25-hectare hexagon grid, which is the target spatial data model for this analysis. Therefore, this data required spatial reaggregation, including detailed information about the location of individual demographic groups of residents. To achieve this, a model of spatial population distribution was developed, assuming that the population of Poland[2] inhabits individual residential buildings proportionally to their usable floor area, with the square meterage of the flat per person varying depending on the type of development and the age of the resident. The official national database of topographic objects (www.geoportal.gov.pl) provides data that distinguish between the functions of buildings, including residential type(b). Based on the available attributes, residential buildings were divided into two categories t: single-family ($t_b = s$) or multi-family ($t_b = m$). The usable area ($Harea_b$) and the number of floor ($Hlevels_b$) of each building were also determined. The estimated usable floor area of individual residential buildings was calculated as follows:

$$A_b = Harea_b \times Hlevels_b$$

The usable floor area of residential building $A_b$along with the attribute of building type t_b was then discretely assigned a presence in space by assigning them to the geometric centroid of the building. Based on this location, each building b obtained an additional spatial attribute r_b, representing the field r, within which its geometric centroid is located. Finally, the total usable floor area of various types of residential building within the reference fields was calculated:

$$A_{t,r} = \sum_{b=1}^{n} A_b \bigwedge b: t_b = t\, , r_b = r$$

where$n$denotes the number of all buildings $b$in the development$t$with a geometric centroid located within field r.

On a national scale, noticeably higher residential floor area per person is observed in areas dominated by single-family housing and in areas with a relatively low percentage of children. Therefore, the average usable area of a dwelling per inhabitant needed to be differentiated based on the age of the resident and the type of development ($W_{d,t}$). The procedure for determining its value proceeded in two phases. In the first phase, the population in each age group residing in each grid cell$r$was allocated to the geometric centroids of the buildings$b$, located there, proportionally to their floor area:

$$Dem_{d,b} = Dem_{d,r} \times \frac{A_b}{\sum_t A_{t,r}} \bigwedge b: r_b = r$$

The average floor area of a dwelling per inhabitant ($W_{d,t}$) was differentiated based on the empirically observed national regularity of the co-occurrence in grid$r$of the population in various age groups $d$with the usable area of dwellings in each type of development$t$. The coefficient values were calculated according to the following formula:

$$W_{d,t} = \frac{\sum_{b=1}^{k} A_b}{\sum_{b=1}^{k} Dem_{d,b}} \bigwedge b: t_b = t$$

Where $k$denotes the number of all buildings $b$in the development $t$in Poland.

In the second phase of the third step, the specific disproportion between the average square meterage in each age group in single-family and multi-family housing (Table 1) was

[2]Despite the analysis being conducted in 5 units (communes) to estimate the population based on building type, national-level dependencies were utilized as they are published in official statistics—hence the references to metric values at the national level.

utilized to determine in each field r the total number of inhabitants in single-family and multi-family housing in the respective age groups:

$$Dem_{d,t,r} = Dem_{d,r} \times \frac{\frac{A_{t,r}}{W_{d,t}}}{\frac{A_{s,r}}{W_{d,s}} + \frac{A_{m,r}}{W_{d,m}}}$$

Tab. 1. The national average residential area per inhabitant in single-family and multi-family housing, by age group.

Age group (d)	$W_{d,s}$ [m^2]	$W_{d,m}$ [m^2]	$\frac{W_{d,s}}{W_{d,m}}$
Under 14	359.665	314.057	1.145
15-64	90.859	67.352	1.349
65 or more	340.347	204.017	1.668

Source: own's elaboration

Next, the inhabitants of each grid cell$r$were reassigned to the individual geometric centroids of the buildings $b$located there. The procedure was carried out independently for the six (d×t) categories of residents:

$$Dem'_{d,b} = Dem_{d,t,r} \times \frac{A_b}{A_{t,r}} \bigwedge b: t_b = t\,, r_b = r$$

As a result, unlike in the first phase, the structure of the population in single and multi-family dwellings differs in each area, with different proportions of each age group in single and multi-family dwellings. The discrete model of spatial distribution of population by age group obtained in this way was again spatially aggregated to the target data model, based on the geometric belonging of the centroids of individual residential buildings to specific hexagon fields h:

$$Dem_{d,t,h} = \sum_{b=1}^{n} A_b \bigwedge b: t_b = t\,, r_b = r$$

3.2 Analytical stage

Considering the adopted research question, it was decided to utilize regression analysis, where the number of Wi-Fi networks per capita served as the dependent variable. Thus, the spatial structure of Wi-Fi networks was explained through explanatory variables, which were the shares of age groups of residents - the youngest and the oldest. The stochastic relationship was determined using multiple regression analysis between the values of two coefficients representing the first ($Rdem_{d,h}$)and one describing the second (Ri_h) of the mentioned characteristics of reference field h. In this study, two independent variables were defined as the percentage of young people:

$$Rdem_{1,h} = \frac{Dem_{1,s,h} + Dem_{1,m,h}}{\sum_{d=1}^{3} Dem_{d,s,h} + Dem_{d,m,h}}$$

And the share of elderly people

$$Rdem_{3,h} = \frac{Dem_{3,s,h} + Dem_{3,m,h}}{\sum_{d=1}^{3} Dem_{d,s,h} + Dem_{d,m,h}}$$

inhabiting the given hexagon h. In the five examined communes, the percentage of population up to 14 years old ranges between 15.1% and 18.02%, while residents aged 65 or older account for between 15.02% and 20.01% there. Meanwhile, in individual hexagons, these values range from 0% to 60% and from 0% to 55.07%, respectively. As a result, the coefficient of variation for the first of these indicators increased from 7.2% to 38.45%, and for the second one from 11.93% to 41.37%.

The dependent variable was defined as the coefficient calculated according to the following formula:

$$Ri_h = \frac{I_h}{\sum_{d=1}^{3} Dem_{d,s,h} + Dem_{d,m,h}}$$

Condition for using linear multiple regression is that the distribution of variables should be approximately normal. Based on the results of the Shapiro-Wilk test (Shapiro et al., 1968), it was found that the distribution of none of the three analysed coefficients meets this condition. Therefore, their values were pre-transformed using specific functions (f_i, f_1, and f_3) to achieve a normal distribution while preserving constant ranks and arithmetic means, and to minimize variation of the standard deviation value. Finally, in this study, the mentioned stochastic relationship is described by a regression function of the following general form:

$$Reg_1(Rdem_{1,h}, Ri_h) = f_{d,1}(Rdem_{1,h}) + f_i(Ri_h) + \varepsilon_i$$

$$Reg_3(Rdem_{3,h}, Ri_h) = f_{d,3}(Rdem_{3,h}) + f_i(Ri_h) + \varepsilon_i$$

The parameters of the function were determined using the Ordinal Least Squares (OLS) method. The analysis was conducted for the set of all h fields located within the territory of the five examined communes, where at least one person resided. Out of 3,480 hexagons with an area of 25 hectares located within the territory of the five examined communes, 36.7%, or 1,276, which are inhabited, were selected for further analysis.

Spatial analysis within step V was conducted in two phases. In the first phase authors focused on explaining the level of the analysed dependencies, whichshould provide an answer to how significant the demographic determinants of spatial variation in Wi-Fi network distribution are at the local level. The second phase aimed to spatially synthesize information about areas with low and high numbers of identified Wi-Fi networks per capita. In the first phase of spatial analysis, the overall stochastic relationship between the distribution of Wi-Fi networks in rural areas and the age structure of residents was utilized in Trend Deviation Analysis, serving as the theoretical reference level for empirical data and their residuals. In each hexagon$h$the local residuals of Ri_h,determined based on data obtained during Wi-Fi network scanning, were calculated from the theoretical value $RiEst_h$derived from the age structure of residents in the given hexagon$h$and the established overall stochastic relationship:

$$\varepsilon_h = Ri_h - RiEst_h$$

Positive deviation was defined as$\varepsilon_h > 0$, while negative deviation was defined as$\varepsilon_h < 0$.

In the second phase of Step V, the results of the regression analysis, together with the results of the residual analysis, were spatially synthesised to build a typology (Stevens, 1946), for which we selected an 'a priori' approach (Johnston, 1976; Mazur, Czapiewski, 2016).Although this approach is more susceptible to subjectivity than a deductive one, it allows for the incorporation of expert knowledge and ensures that the substantive and cognitive output aligns better with the research aim. This output, defined here as the spatial co-occurrence of the local age structure of rural residents with the number of Wi-Fi networks in relation to demographic structure, led to the establishment of a typology to categorize each hexagon$h$ into one of four area types:

- 'vital' ($RiEst_h \geq \overline{RiEst_h} \cap \varepsilon_h \geq 0$);
- 'lagged' ($RiEst_h \geq \overline{RiEst_h} \cap \varepsilon_h < 0$);
- 'inspired' ($RiEst_h < \overline{RiEst_h} \cap \varepsilon_h \geq 0$);
- 'left-behinded' ($RiEst_h < \overline{RiEst_h} \cap \varepsilon_h < 0$).

The 'vital' areas are settled by relatively young people, where there is also a high number of Wi-Fi networks. The 'lagged' areas show a relatively small number of networks when compared to the young age structure. The 'inspired' type shows a high number of Wi-Fi networks despite a relatively older age structure. The last type, 'left-behind', indicates that the area has a low number of networks, with a relatively older population.

4. Results

4.1. Wi-Fi Networks and Age Structure

Data from Table 2 indicates significant differentiation among the examined communes in terms of basic parameters describing their characteristics. The largest commune in terms of area - Suwałki is the second largest commune in terms of population included in the study, and it is characterized by the lowest population density and road density. Bierutów commune has the largest population, while Orońsko commune has the highest population density and road density. It is a small commune - almost twice the size of the next smallest commune in the comparison - Bierutów.

Tab. 2.Basic Statistical Data for Case Studies

communes	Area [km^2]	The number of inhabitants	Populationdensity	Density of roads km/km^2	The share of population in multi-family housing	The share of residents in the pre-working age group	The average download speed by Ookla [Mbps]	The number of scanned Wi-Fi network
Bierutów	147.0	9163	62	3.9	38.2	15.1	13.6	2075
Kuślin	151.7	7088	47	4.0	8.5	15.5	21.2	690
Orońsko	82.0	5962	73	5.2	5.1	18.0	10.5	999
Suwałki	264.6	7675	29	3.8	5.9	17.4	24.2	1850
Szadek	106.5	5191	49	4.0	16.1	17.8	88.8	1735

Source: own's elaboration

The age structure of residents in each commune varies significantly (see Table 3). Furthermore, the application of the previously described procedure for aggregating demographic data, and consequently the obtained differentiation of the area per capita for individuals of a certain age (d) residing in a specific type of housing (t_b) (see Tab. 1), has shown that the age structure of residents in single-family and multi-family housing also differs significantly in each of them (tab. 3). For example, while in the commune of Suwałki the proportion of younger and older people living in single-family and multi-family dwellings is very similar, in the commune of Orońsko the inhabitants of multi-family dwellings are significantly older.

Tab. 3. The share of the population in three age groups by types of buildings [%]

	$t_b = s$			$t_b = m$		
	$d = 1$	$d = 2$	$d = 3$	$d = 1$	$d = 2$	$d = 3$
Bierutów	10.1	41.2	10.6	5.0	24.9	8.3
Kuślin	14.4	59.0	18.0	1.0	5.5	2.0
Orońsko	17.5	62.8	14.6	0.6	3.2	1.4
Suwałki	16.4	63.6	14.1	1.0	4.0	0.9
Szadek	15.3	56.3	12.3	2.4	10.8	2.9

Source: own's elaboration

Based on the preliminary characterization of the hexagons, it can already be observed that the number of Wi-Fi networks per capita is relatively higher in areas inhabited by younger populations (Fig. 5). The influence of age structure appears to be equally significant for both variables considered in this study: the indicator $Rdem_{1,h}$reflecting the percentage of the youngest population, and the indicator $Rdem_{3,h}$representing the proportion of elderly population (Fig. 6).

The final answer to the RQ, namely whether the number of Wi-Fi networks per capita (〖Ri〗 _h) is dependent on age structure, was provided by the multiple regression analysis. The result is the following function:

$$f_i(Ri_h) = 0{,}185 \times f_1(Rdem_{1,h}) - 0{,}652 \times f_3(Rdem_{3,h}) + 0{,}281 + \varepsilon_h$$

The coefficients of the model confirm the assumption that the number of Wi-Fi networks per capita is higher in areas where a relatively larger proportion of young people reside, and lower in areas with a higher proportion of elderly residents. However, to consider such a result credible, the strength and significance of this statistical relationship needed to be determined.

The correlation coefficient values indicate that demographic factors alone are not a sufficient explanatory factor for the distribution of Wi-Fi networks in the analysed rural areas. The Pearson linear correlation coefficient value for the result of the regression function $f_i(Ri_h)$is 0.109. However, it should be emphasized that the sample size of the analyzed reference fields ($n = 1\ 276$) is sufficient for the obtained result to serve as the basis for answering the RQ regarding the existence of a statistical relationship between the demographic structure of residents and the occurrence of Wi-Fi networks. Its marginal level of significance (p-value) is p=0.01%.

4.2 Spatial analysis

The distribution of Wi-Fi networks within the case studies (communes) closely correlates with the distribution of inhabitants. The correlation coefficient for hexagons between the number of Wi-Fi and the number of inhabitants is 0.88. Consequently, the highest density of networks per hexagon is typically found in the centers of larger towns/villages and along main streets. One notable exception to this general pattern is the suburban commune of Suwałki, where the spatial structure of residential development (settlement network) is the most dispersed. Relatively high numbers of Wi-Fi networks are also found there away from the town centers.

Although the overall number of identified networks varies significantly across communes when adjusted for the population, ranging from less than 0.1 network in Kuślin to over 0.3 in Szadek, it reflects a highly diverse internal situation. It is noteworthy that in each commune, most Wi-Fi networks were identified primarily in areas with residential development. Outside these densely populated areas, there are typically fewer Wi-Fi networks.

However, even when considering the number of Wi-Fi networks per capita, both low and high values of Ri_hcan still be found in each commune (Fig. 5). Similarly, across the predominant areas of individual communes, the indicator value remains relatively low, with areas with above-average values occupying a smaller area, typically outside the town center and in areas with low population density.

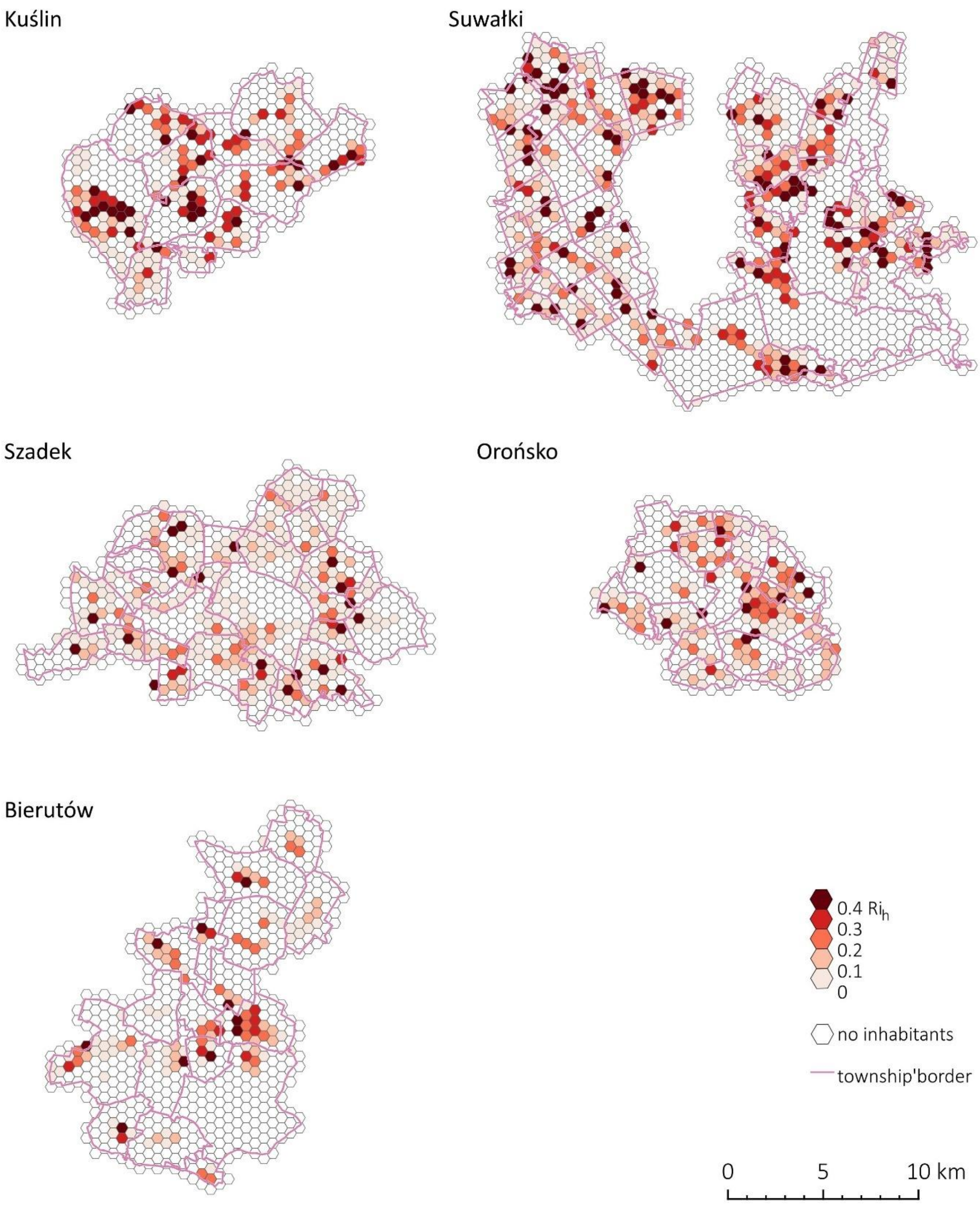

Fig. 5 The number of Wi-Fi networks per capita (Ri_h) in analysed communes
Source: own's elaboration

The results also indicate that the number and distribution of Wi-Fi networks are similar in administrative centers (where the highest indicator values within the commune are recorded), while greater variability is observed in smaller or peripheral towns/villages (see fig. 2). Thus, higher population density is associated with a greater number of Wi-Fi networks. However, another contributing factor may be the type of residential development (single-family and multi-family).

The distribution of the indicator value $RiEst_h$ indicates in which parts of the communes and individual towns there would be a low or high number of Wi-Fi networks, assuming that it results solely from the age structure of the residents (fig. 6). A low value of the indicator occurs in areas mainly inhabited by older people, especially in the 65+ age group, while a high value is observed where this generation constitutes a smaller percentage of the population. Analysis of the regression residuals provided very interesting information (Figure 7), indicating areas where other potential factors of spatial variation in Wi-Fi networks may be present.

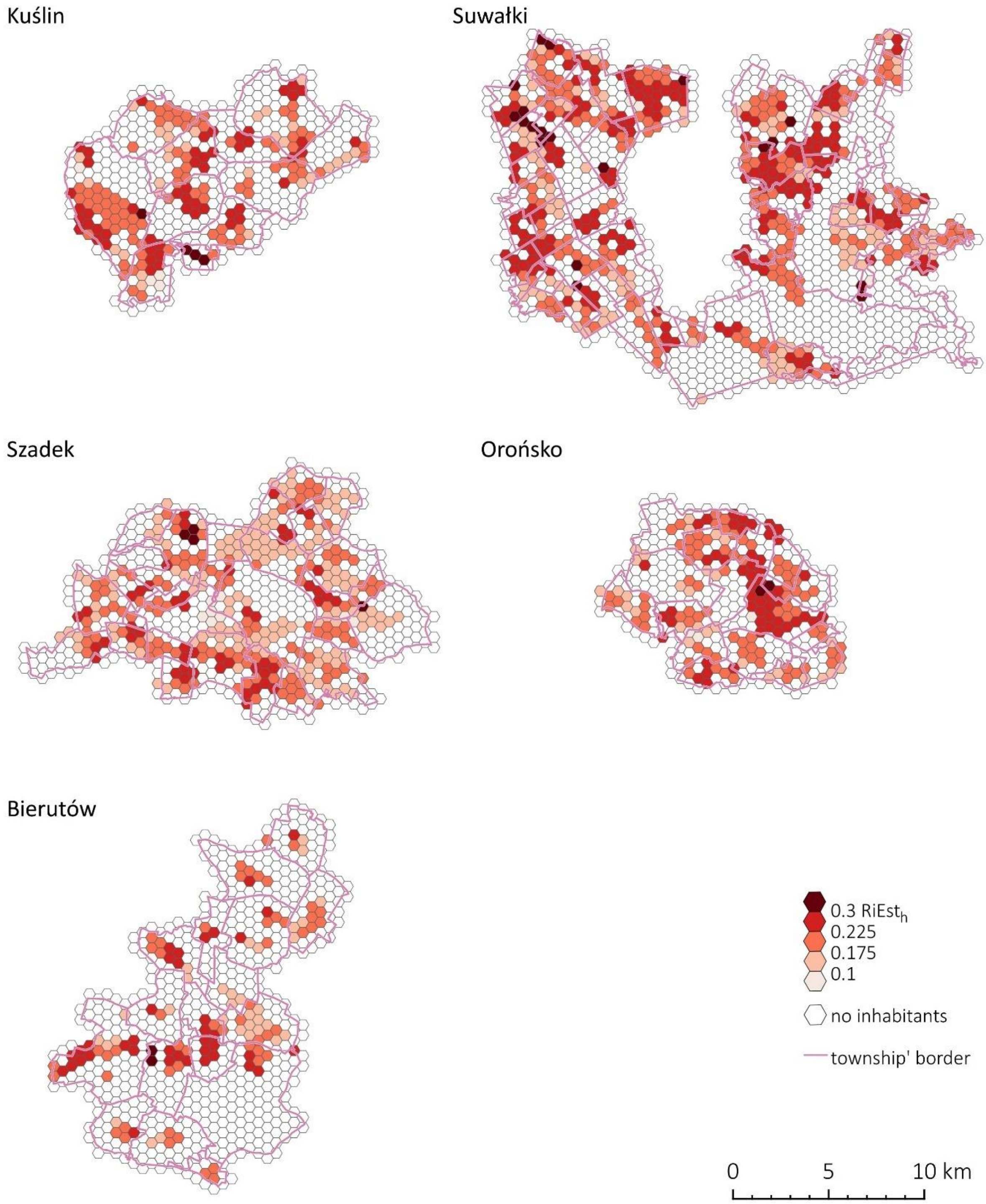

Fig. 6 Wi-Fi networks per capita resulting from age structure ($RiEst_h$)
Source: own's elaboration

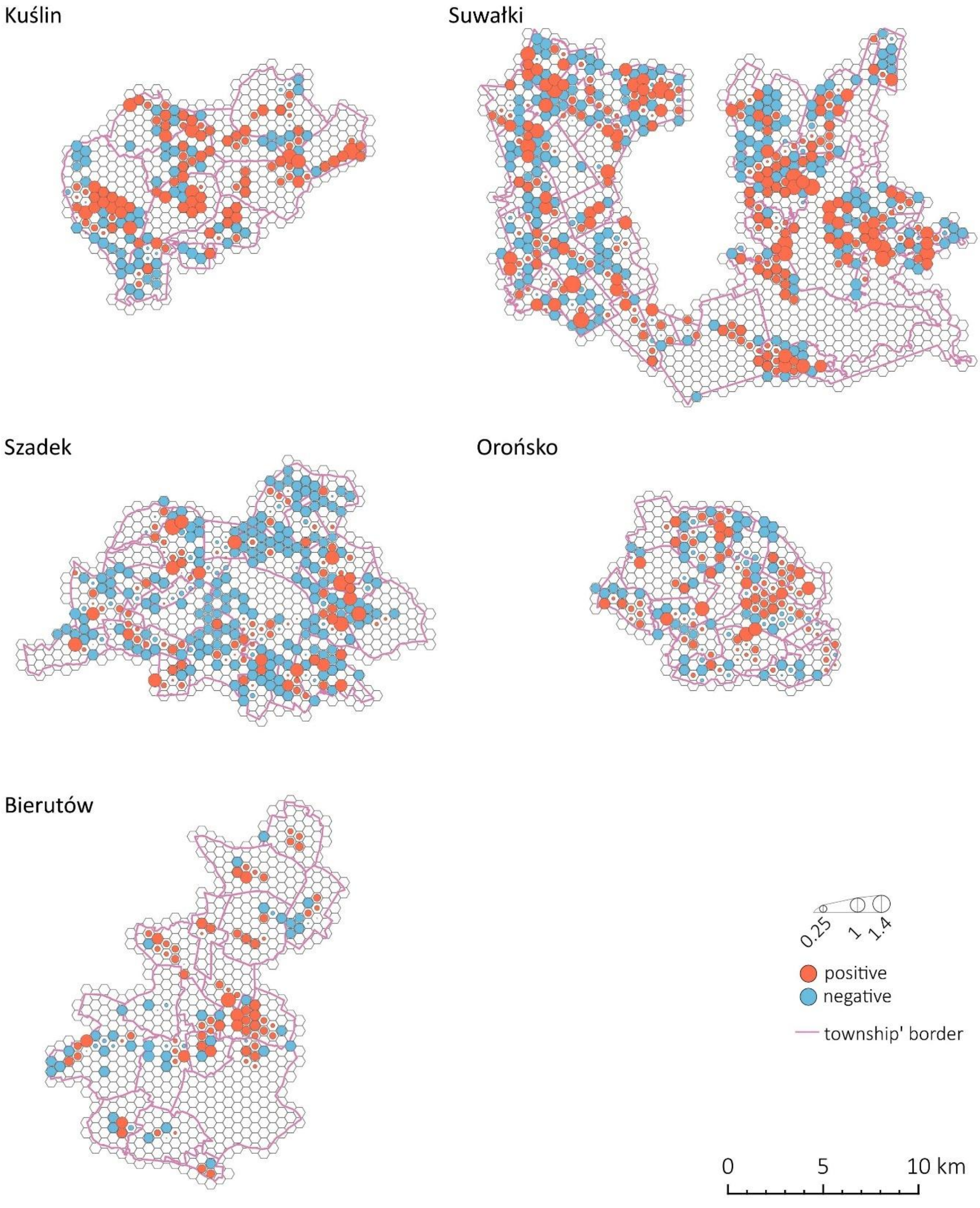

Fig. 7 Regression residuals in analysed communes (ε_h)
Source: own's elaboration

The typology (Fig. 8) provides a synthetic view of the results presented in Figs. 6 and 7, serving as their summary. It is worth noting that individual types of areas form distinct clusters.

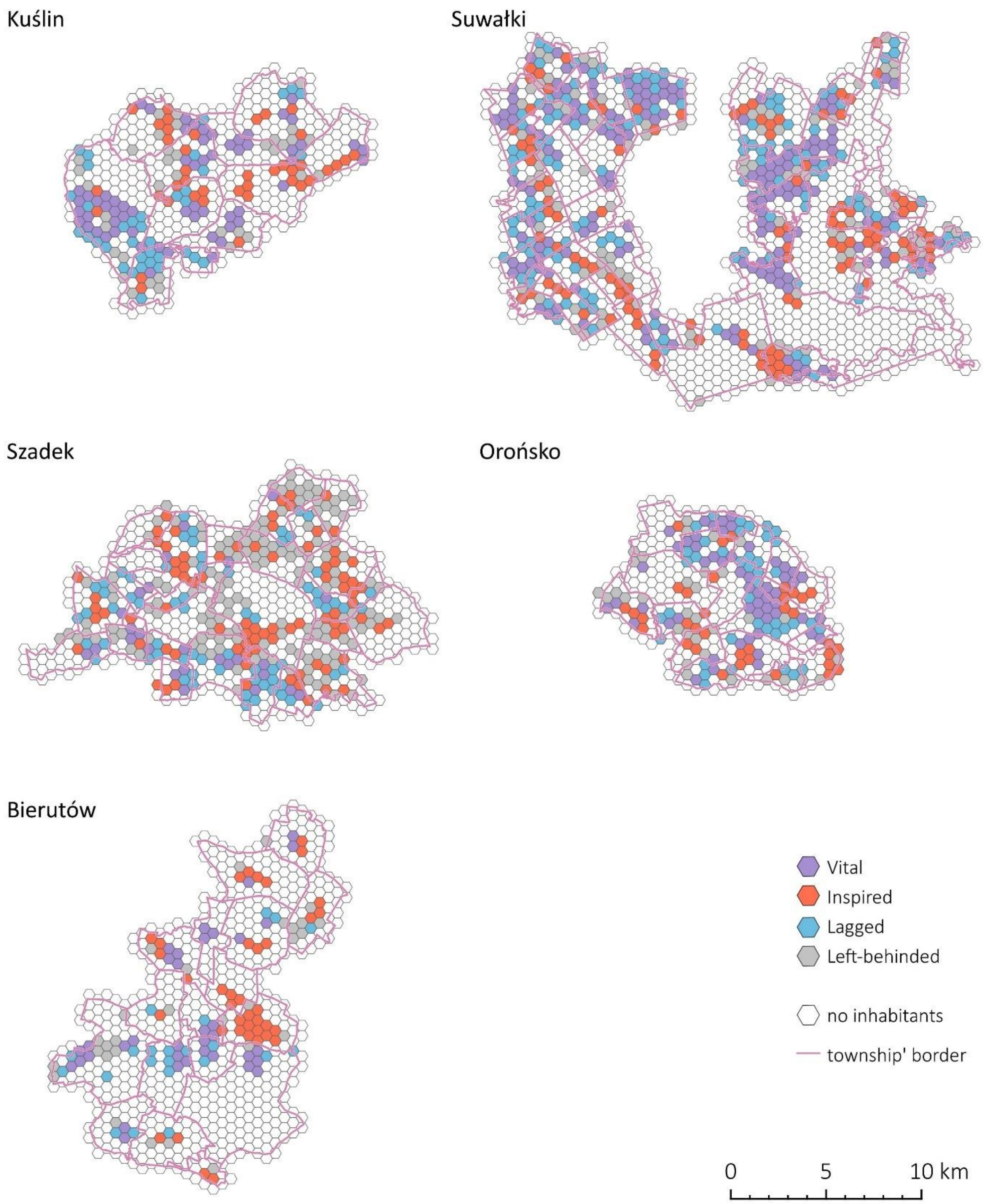

Fig. 8.Typology based on the age structure of rural residents and the number of Wi-Fi networks
Source: own's elaboration.

5. Discussion and Conclusion

The analysis of the distribution of Wi-Fi networks in rural areas has made it possible to identify significant features at the intersection of real and digital space. One important finding is the overall strong correlation between population and the number of Wi-Fi networks. The widespread use of Wi-Fi for internet connectivity, integrated into daily life, means that Wi-Fi networks are only found within built-up areas and are absent in uninhabited or non-commercial areas. Wi-Fi usage is common not only in urban but also in rural areas. Therefore, based on our research encompassing rural areas with varying internet performance and proximity to large cities across different regions of the country, we concluded that the strength of relationship between people and Wi-Fi networks does not depend on the type of area or its specific characteristics. This leads to the significant observation of the universality or ubiquity of digital devices shaping access to the digital realm. Consequently, we could verify that even at the local level, smart spaces emerge, facilitated by hidden gateways.

Based on the research and analysis conducted, we have successfully addressed the research question: the spatial distribution of Wi-Fi networks is closely linked to the spatial distribution of younger age groups. This confirms issues related to digital divide (McConnell, Straubhaar, 2015), especially in terms of varying digital competencies (Brandtzæg et al., 2011; Hargittai, 2002), as well as needs. It is important to emphasize that for the elderly population, age structure factor acts as a barrier due to the lack of appropriate digital skills or perceived needs related to internet use. Regarding areas inhabited by the youngest population group, it should be noted that they are active internet users and often reside in households with adults who are likely to be professionally active and familiar with digital technologies. In this context, we can refer to the research by Reisdorf et al. (2022), who indicated that families with children engage in a wide range of online activities, which undoubtedly positively affects the presence of Wi-Fi networks.

The conducted study fills an important gap in studies on the local dimension of variations related to access and use of digital technologies in rural areas. This relatively underexplored issue in spatial research is crucial for understanding the relationship between physical and digital space. While one might assume that the significance of Wi-Fi networks will diminish with technological advancements in internet access. Nevertheless, as indicated by Oughton et al. (2021), this technology continues to evolve and remains essential for meeting people's internet connectivity needs, especially for indoor use.

Undoubtedly, the presented results also provide significant grounds for formulating directions for further research. Firstly, the identification of certain common features linking areas of positive or negative deviations from the regression constitutes valuable information, indicating other potential factors contributing to spatial variations in Wi-Fi networks. Therefore, analyses based on a broader spectrum of socio-demographic characteristics should be conducted, although this may not always be feasible due to limited spatial resolution. Secondly, recognizing spatial patterns based on scanning should be complemented by social research, i.e., identifying the causes/methods/conditions of Wi-Fi usage by residents. This should provide a comprehensive understanding of the functioning, use and dependence of rural communities on hidden gateways.

Literature

Albino, V., Berardi, U., & Dangelico, R. M. (2015). Smart cities: Definitions, dimensions, performance, and initiatives. *Journal of Urban Technology*, 22(1), 3-21.

Aoyama, Y., & Sheppard, E. (2003). The dialectics of geographic and virtual space. *Environment and Planning A*, 35(7), 1151-1156.

Ash, J., Kitchin, R., & Leszczynski, A. (2018). Digital turn, digital geographies?. *Progress in Human Geography*, 42(1), 25-43.

Birnbaum, L., Wilhelm, C., Chilla, T., & Kröner, S. (2021). Place attachment and digitalisation in rural regions. *Journal of Rural Studies*, 87, 189-198.

Blake, E. (2002). Spatiality past and present: an interview with Edward Soja, Los Angeles, 12 April 2001. *Journal of Social Archaeology*, 2(2), 139-158.

Blank, G., & Dutton, W. H. (2014). Next Generation Internet Users. In Society and the Internet. How Networks of Information and Communication are Changing Our Lives, edited by M. Graham and W.H. Dutton, 37-52. Oxford: Oxford University Press.

Boos, T. (2017). Inhabiting Cyberspace and Emerging Cyberplaces. The Case of Siena, Italy. Palgrave Macmillan, Cham.

Brandtzæg, P. B., Heim J., Karahasanović A. (2011). Understanding the new digital divide – A typology of Internetusers in dEurope, *International Journal of Human-Computer Studies* 69, 3, pp. 123–138.

Buzzelli, M. (2020). Modifiable areal unit problem. *International encyclopedia of human geography*, 169.

Birch C. P. D., Oom S. P., Beecham J. A. (2007). Rectangular and hexagonal grids used for observation, experiment and simulation in ecology, *Ecological Modelling*,206, 3–4, 347-359

van Deursen A. J., Helsper, E.J. (2015). The third–level digital divide: who benefits most from being online?, Communication and Information Technologies Annual, 10, 29–52.

Driskell L., Wang F. (2009). Mapping digital divide in neighborhoods: Wi–Fi access in Baton Rouge, Louisiana. *Annals of GIS*, 15, 1, 35–46.

Elena-Bucea, A., Cruz-Jesus, F., Oliveira, T., & Coelho, P. S. (2021). Assessing the role of age, education, gender and income on the digital divide: Evidence for the European Union. *Information Systems Frontiers*, 23, 1007-1021.

ElMassah, S., & Mohieldin, M. (2020). Digital transformation and localizing the sustainable development goals (SDGs). *Ecological Economics*, 169, 106490.

Etta, V. O., Sari, A., Imoize, A. L., Shukla, P. K., &Alhassan, M. (2022). Assessment and Test-case Study of Wi-Fi Security through the Wardriving Technique. *Mobile Information Systems*, 2022.

Forlano, L. (2009). WiFi geographies: When code meets place. *The Information Society*, 25(5), 344-352.

Frankfort-Nachmias C., Nachmias D., DeWaard J. (2014). *Research Methods in the Social Sciences*, WorthPublishers.

Fuentes–Bautista M., Inagaki N. (2006). Reconfiguring public Internet access in Austin, TX: Wi–Fi'spromiseand broadband divides, *Government Information Quarterly*, 23, 3–4, 404–434.

Gorman, S.P. & Malecki, E.J. (2000) The networks of the Internet: an analysis of provider networks in the USA, *Telecommunications Policy*, 24, pp. 113-134.

Grubesic, T.H. & O'Kelly, M.E. (2002) Using Points of Presence to Measure Accessibility to the Commercial Internet, *The Professional Geographer*, 54, pp. 259-278.

Grubesic T.H., Murray A.T. (2004). „Where" Matters: Location and Wi–Fi Access, *Journal of Urban Technology*, 11, 1, 1–28.

Haight, M., Quan-Haase, A., & Corbett, B. A. (2016). Revisiting the digital divide in Canada: The impact of demographic factors on access to the internet, level of online activity, and social networking site usage. In Current Research on Information Technologies and Society (pp. 113-129). Routledge.

Harvey, D. (2012). From space to place and back again: Reflections on the condition of postmodernity. in Mapping the futures (pp. 2-29). Routledge.

Hargittai E. (2002). Second–Level Digital Divide: Mapping Differences in People's Online Skills, First Monday, 7, 4.

ITU, (2024). International Telecommunication Union, www.itu.int (access: 06.05.2024)

Janc, K., Ilnicki, D., & Jurkowski, W. (2022). Spatial regularities in Internet performance at a local scale: The case of Poland. *Moravian Geographical Reports*, 30(3), 163-178.

Johnston, R. J. (1976). Classification in Geography. Concepts and techniques in Modern Geography 6. Norwich: Geo Abstracts Ltd.

Kamienski, C., Ratusznei, J., Trindade, A., &Cavalcanti, D. (2020). Profiling of a large-scale municipal wireless network. *Wireless Networks*, 26, 5223-5253.

Kellerman, A. (2020). Is cyberspace there after all?. In Geographies of the Internet (pp. 19-33). Routledge.

Kim, Y. L. (2018). Seoul's Wi-Fi hotspots: Wi-Fi access points as an indicator of urban vitality. Computers, *Environment and Urban Systems*, 72, 13-24.

Komorowski, Ł., &Stanny, M. (2020). Smart villages: Where can they happen?. Land, 9(5), 151.

Konomi S. I., Sasao T., Hosio S., Sezaki K., (2019). Using ambient WiFi signals to find occupied and vacant houses in local communities. *Journal of Ambient Intelligence and Humanized Computing*, 10, 2, 779-789.

Kosari, M., & Amoori, A. (2018). Thirdspace: The trialectics of the real, virtual and blended spaces. *Journal of Cyberspace Studies*, 2(2), 163-185.

Lee H.J., Park N., Hwang Y., (2015). A new dimension of the digital divide: Exploring the relationship between broadband connection, smartphone use and communication competence. *Telematics and Informatics*, 32, 1, 45–56.

Louw, C., & Von Solms, B. (2019). Free public Wi-Fi security in a smart city context—An end user perspective. In Smart Cities Cybersecurity and Privacy (pp. 113-127). Elsevier.

Li, R., Chen, K., & Wu, D. (2020). Challenges and Opportunities for Coping with the Smart Divide in Rural America. *Annals of the American Association of Geographers*, 110(2), 559–570.

Magnusson, D., Hermelin, B. (2019). ICT development from the perspective of connectivity and inclusion–the operation of a local digital agenda in Sweden. *Norsk Geografisk Tidsskrift*, 73(2), 81–95.

Massey, D. (2013). Space, place and gender. John Wiley & Sons.

Mazur, M. and Czapiewski, K. (2016). Functional structure of gminas in Poland – classification approaches and research opportunities. [in:] M. Wójcik and K. Czapiewski (eds.) Multifunctional development in rural spaces: challenges for policy and planning. *Studia Obszarów Wiejskich*, 43, 7–22.

McConnell, C., &Straubhaar, J. (2015). Contextualizing open wi-fi network use with multiple capitals. In *Communication and information technologies Annual* (Vol. 10, pp. 205-232). Emerald Group Publishing Limited.

McShane, I., & Grechyn, V. (2019). Public Wi-Fi provision by Australian local government authorities. *Australian Journal of Public Administration*, 78(4), 613-630.

Merriman, P., Jones, M., Olsson, G., Sheppard, E., Thrift, N., & Tuan, Y. F. (2012). Space and spatiality in theory. *Dialogues in Human Geography*, 2(1), 3-22.

Metta, M., Ciliberti, S., Obi, C., Bartolini, F., Klerkx, L., & Brunori, G. (2022). An integrated socio-cyber-physical system framework to assess responsible digitalisation in agriculture: A first application with Living Labs in Europe. *Agricultural Systems*, 203, 103533.

Morris, J., Morris, W., & Bowen, R. (2022). Implications of the digital divide on rural SME resilience. *Journal of Rural Studies*, 89, 369-377.

Naldi, L., Nilsson, P., Westlund, H., &Wixe, S. (2015). What is smart rural development?. *Journal of Rural Studies*, 40, 90-101.

Nam, T., & Pardo, T. A. (2011). Conceptualizing smart city with dimensions of technology, people, and institutions. In Proceedings of the 12th annual international digital government research conference: digital government innovation in challenging times (pp. 282-291).

Oughton, E. J., Kusuma, J., Peyronel, T., & Crowcroft, J. (2021). Wi-Fi wardriving studies must account for important statistical issues. arXiv preprint arXiv:2101.06301.

Oughton, E. J., Lehr, W., Katsaros, K., Selinis, I., Bubley, D., & Kusuma, J. (2021). Revisiting wireless internet connectivity: 5G vs Wi-Fi 6. Telecommunications Policy, 45(5), 102127.

Overton, W.S., White, D., Stevens Jr., D.L. (1990). Environmental monitoring and assessment program: design report. Report No. EPA/600/3-91/053, U.S. Environmental Protection Agency, Environmental Monitoring and Assessment Program, Washington, DC, 52 pp.

Pahlavan, K., Krishnamurthy, P. (2021). Evolution and Impact of Wi-Fi Technology and Applications: A Historical Perspective. Int J Wireless Inf Networks 28, 3–19.

Perng, S. Y. (2015). Performing tasks with wi-fi signals in Taipei. *Space and Culture*, 18(3), 285-297.

Ratti C., Claudel M. (2016). The City of Tomorrow: Sensors, Networks, Hackers, and the Future of Urban Life. Yale University Press, New Haven.

Reisdorf, B. C., Fernandez, L., Hampton, K. N., Shin, I., & Dutton, W. H. (2022). Mobile phones will not eliminate digital and social divides: How variation in Internet activities mediates the relationship between type of Internet access and local social capital in Detroit. *Social Science Computer Review*, 40(2), 288-308.

Salemink, K., Strijker, D., & Bosworth, G. (2017). Rural development in the digital age: A systematic literature review on unequal ICT availability, adoption, and use in rural areas. Journal of Rural Studies, 54, 360-371.

Santos, F., Pesantes, P., & Bonilla-Bedoya, S. (2021). Exploring wardriving potential in the Ecuadorian Amazon for indirect data collection. In IOP Conference Series: Earth and Environmental Science (Vol. 690, No. 1, p. 012054). IOP Publishing.

Shapiro, S. S., Wilk, M. B., & Chen, H. J. (1968). A comparative study of various tests of normality. *Journal of the American Statistical Association*, 63, 1343-1372.

Soja, E. W. (1989). Postmodern geographies: The reassertion of space in critical social theory. Verso.

Soja, E.W. (2008). Thirdspace: Toward a new consciousness of space and spatiality. In Communicating in the third space (pp. 63-75). Routledge.

StephensM., Poorthuis, A. (2015). Follow the Neighbour: Connecting the Social and the Spatial Networks on Twitter, Computers, *Environment and Urban Systems*, 53, pp. 87–95.

Streitz, N. (2019). Beyond 'smart-only' cities: redefining the 'smart-everything' paradigm. Journal of Ambient Intelligence and Humanized Computing, 10(2), 791-812.

Tang, X., Tan, Z., Hu, S., &Geng, H. (2019). Evaluating spatial service and layout efficiency of municipal Wi-Fi facilities for Smart City planning: A case study of Wuhan city, China. *Socio-Economic Planning Sciences*, 65, 101-110.

Thomas, J., Wilken, R., & Rennie, E. (2021). Wi-Fi. John Wiley & Sons.

Torrens, P. M. (2008). Wi-Fi geographies. *Annals of the Association of American Geographers*, 98, 1, 59-84.

Tranos, E. (2013). The geography of the internet: Cities, regions and internet infrastructure in Europe. Edward Elgar Publishing.

Tsui, A. W. T., Lin, W. C., Chen, W. J., Huang, P., & Chu, H. H. (2010). Accuracy performance analysis between war driving and war walking in metropolitan Wi-Fi localization. *IEEE Transactions on Mobile Computing*, 9(11), 1551-1562.

Ylipulli, J., Suopajärvi, T., Ojala, T., Kostakos, V., & Kukka, H. (2014). Municipal WiFi and interactive displays: Appropriation of new technologies in public urban spaces. *Technological Forecasting and Social Change*, 89, 145-160.

Wang, M., Liao, F. H., Lin, J., Huang, L., Gu, C., & Wei, Y. D. (2016). The making of a sustainable wireless city? Mapping public Wi-Fi access in Shanghai. *Sustainability*, 8(2), 111.

Whitacre, B.E. & Mills, B.F. (2007) Infrastructure and the Rural-urban Divide in High-speed Residential Internet Access, *International Regional Science Review*, 30, pp. 249-273.

Wolfert, S., Ge, L., Verdouw, C., &Bogaardt, M. J. (2017). Big data in smart farming–a review. *Agricultural systems*, 153, 69-80.

Wolski, O., & Wójcik, M. (2019). Smart villages revisited: Conceptual background and new challenges at the local level. In Smart Villages in the EU and Beyond (pp. 29-48). Emerald Publishing Limited.

Zook, M. A., Graham, M. (2007). Mapping DigiPlace: geocoded Internet data and the representation of place. *Environment and Planning B: Planning and Design*, 34: 466–482.