Cluster-Based Strategies for Enhancing BTS Infrastructure and Cellular Signal Coverage in Indonesian Villages

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Abstract. This study investigates the enhancement of Base Transceiver Station (BTS) infrastructure and cellular signal coverage in Indonesian villages from 2021 to 2023. Provinces were classified using clustering techniques into three distinct groups: high-performing provinces (Cluster 0), underserved areas (Cluster 1), and moderately performing regions (Cluster 2). Advanced telecommunication strategies, such as Intelligent Reflecting Surfaces (IRS), UAV-assisted connectivity, and cognitive Device-to-Device (D2D) communication, were incorporated into tailored yearly strategies for each cluster. The findings highlight that IRS deployment, coupled with satellite and UAV solutions, can significantly enhance connectivity in underserved areas. These strategies aim to bridge Indonesia's digital divide, ensure equitable access to reliable communication services, and foster sustainable development in rural areas.

Keywords: BTS Infrastructure, Cellular Signal, Clustering, Intelligent Reflecting Surfaces, Telecommunication Strategy.

1. Introduction

In Indonesia, moving forward between the years 2021 and 2023, the improvement and provision of cellular signal coverage in Indonesian villages through the enhancement of Base Transceiver Station (BTS) infrastructure has become critically necessary within the telecommunication sector. Various modalities have emerged with the advent of advanced technologies such as Intelligent Reflecting Surfaces (IRS) and user-density-based optimization techniques to address these challenges.

One such modality is the employment of IRS technologies, which enhance signal coverage and quality. IRSs achieve this by using reflected signals to reach obstructed users, especially in scenarios lacking a direct line of sight. Researchers have confirmed that integrating IRSs can expand coverage in millimeter-wave and terahertz networks, where conventional signal paths are often obstructed (Ghatak et al., 2021; Kassem et al., 2023). By altering the phase and amplitude of incoming signals, IRSs create more favorable communication conditions, significantly improving network performance (Sun et al., 2021). This capability is particularly relevant in Indonesia, where geographical barriers hinder effective signal propagation.

In addition, optimizing BTS deployment by adjusting its configuration relative to user density and geographic layout has proven effective. Studies have shown that modifying antenna tilting and aligning BTS densities with the nominal coverage area of users can significantly increase the signal-to-interference-plus-noise ratio (SINR) and coverage probability (Samal et al., 2023). This approach reduces resource inefficiencies and caters to the varying user densities common in rural communities, especially during diurnal extremes.

Finally, the strategy of using airborne platforms, such as drones equipped with IRS, has been proposed to enhance coverage in hard-to-reach areas. These platforms provide additional capacity and address coverage gaps, particularly in regions lacking physical infrastructure (Li et al., 2022). UAVs, with their maneuverability, can bridge shortfalls and ensure continuous services in rural and remote areas.

Furthermore, the deployment of advanced communication techniques, such as cognitive Device-to-Device (D2D) communication, presents a promising solution for alleviating coverage gaps. D2D allows devices to communicate directly without relying on BTS infrastructure, making it particularly advantageous in rural areas with limited connectivity (Iqbal et al., 2021).

2. Methods

2.1 Clustering Techniques

Clustering is helpful in forming groups of regions that share similar attributes. For this task of province classification according to signal coverage shapes, the K-Means algorithm which is quite common because of its efficient use was used. To evaluate the true number of clusters, the Elbow method was employed making sure there is a good trade-off between separation and compactness of clusters (Kodinariya & Makwana, 2013). As noted in telecommunications research, this method indeed works well and allows exploring the spatial characteristics of network elements distribution (Mahmud et al., 2024; Samal et al., 2023).

2.2 Dimensionality Reduction

To display the clusters information in two-dimensions, Principal Component Analysis (PCA) was used. PCA is a common technique in the field of statistics whereby Colombian data are being scrambled and such that the majority of the variance will be still preserved in the display. The telecommunication industry has also used it in the past to enhance clustering results (Sun et al., 2021).

2.3 Data Normalization

In order to have fair comparisons between the provinces, the features such as the number of villages with strong, weak and with no signal were standardized using the standard scaler. Such a stage is very frequent in clustering studies whereby the data is centered at the mean and detached from unit which is a typical clustering stage to eliminate distortions caused by the differences in magnitude of the samples (Aggarwal & Reddy, 2013).

2.4 Advanced Telecommunication Strategies

In addition to clustering, this study incorporates advanced telecommunication strategies:

1. **Intelligent Reflecting Surfaces (IRS):** It has been suggested that IRS technology which operates through electric surfaces to change the signal routes may offer a possible method to enhance the signal in obstructed environments (Sun et al., 2021). Other studies suggest that IRS technology can play a crucial role in extending network range in non-urban and harsh settings (Ghatak et al., 2021; Kassem et al., 2023).
2. **User-Density Optimization:** Utilizing user concentration levels in determining the positioning of Base Transceiver Stations (BTS) is an effective strategy. Changes in antenna angles and on-demand deployment of base stations are said to be effective measures for increasing the signal-to-interference-minus-noise ratio (SINR) and the coverage probability (Chaoub et al., 2022; Samal et al., 2023)
3. **Unmanned Aerial Vehicles (UAVs):** The employment of UAVs with IRS has become a versatile means of increasing coverage in hard-to-reach areas. Their mobility supports the ability to react dynamically to coverage voids especially in areas where the conventional infrastructure is lacking (Li et al., 2022).
4. **Cognitive Device to Device (D2D) Communication:** Direct interface of device to device communication facilitates seamless interactions onsite which eliminates the need to go through the central BTSs . This method enables enhancement of coverage and blind spot provisions and has been studied in connection with 5G networks (Iqbal et al., 2021).

2.5 Data Sources

The dataset includes:

1. Number of villages with BTS infrastructure categorized as strong, weak, and no signal for the years 2021–2023.
2. Provincial-level data from Indonesian telecommunication reports.

2.6 Analytical Framework

The analysis followed these steps:

1. **Data Normalization**: Preparing data for clustering (Kumar & Sinha, 2020).
2. **Clustering**: Applying K-Means with optimal clusters determined by the Elbow Method (Rahayu et al., 2021).
3. **Visualization**: Using PCA to interpret cluster separations.
4. **Trend Analysis**: Evaluating yearly trends for each signal category across clusters (Singh et al., 2022).

5. **Strategy Formulation**: Integrating advanced technologies into actionable plans tailored to each cluster.

3. Result

3.1 Cluster Identification

Provinces were classified into three clusters:

- **Cluster 0**: High-performing provinces with strong signal coverage and minimal weak/no signal issues.
- **Cluster 1**: Underserved areas requiring urgent infrastructure deployment.
- **Cluster 2**: Moderately performing provinces needing signal quality improvements.

Provinces were grouped into three clusters (strong, weak, and no signal) according to the longitude of coverage (strong, weak, and no signal). Based on the ratio of the total cost of different configurations for all clusters, the optimal number of cluster was identified using the Elbow Method. This is graphically depicted in the figure 1 to enable quick identification of the 'elbow' point which shows the best suited number of configurations needed.

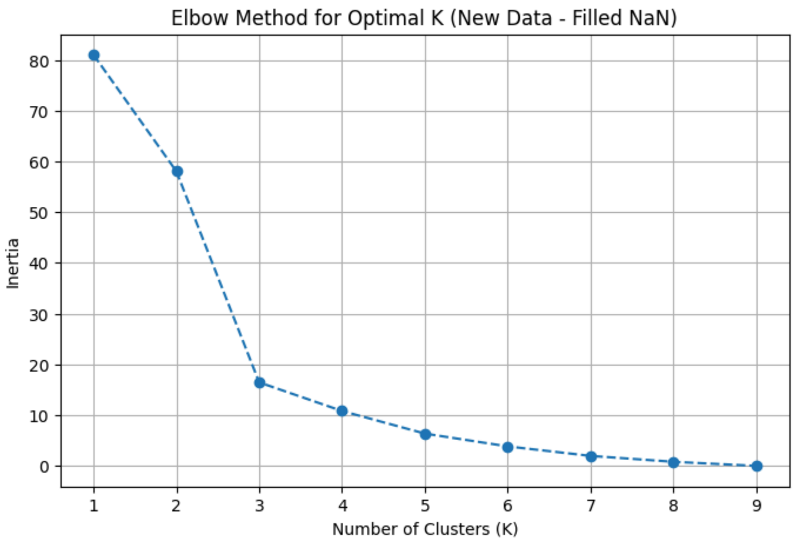

Figure 1: Elbow Method to Determine Optimal Clusters

Once the clustering had occurred, the data was reduced in dimension to visualize the important features through the use of Principal Component Analysis (PCA). The clusters were affixed in a two-dimensional space so as to better illustrate the distinct regions of the clusters as in figure 2.

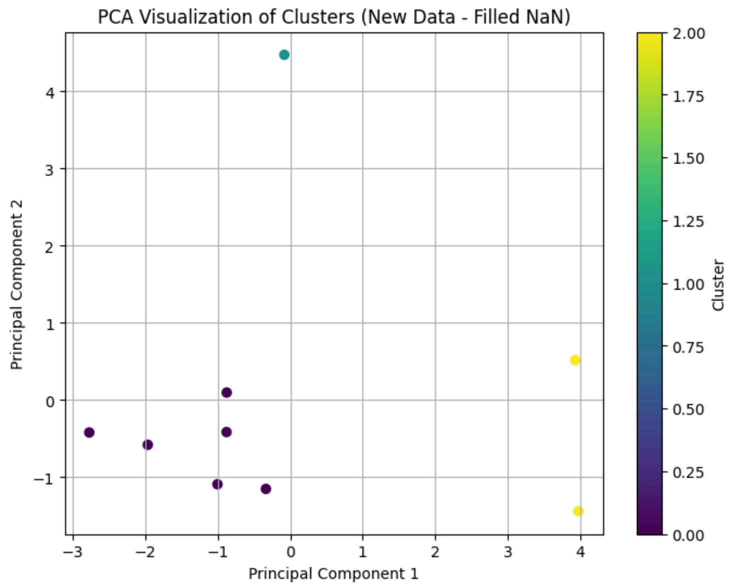

Figure 2: PCA Visualization of Clusters

3.2 IRS Adoption Trends

The deployment of Intelligent Reflecting Surfaces (IRS) experienced a discrepancy between both clusters between the years 2021 and 2023 according to Fig.1. Valid provinces identified as cluster 0 have increased their adoption steadily with over 10%, 30% and 50% being the adoption in the years 2021, 2022 and 2023 respectively. This cluster concentrated on deploying IRS, addressing the requirements for 5G and enhancement of already deployed networks. Weak zone cluster 1 had the highest growth reaching the peak of 80% from 20% in 2021 to 80% in 2023. The rapid rate of progression is reflective of the demand for enhanced network provision within locations that experience substantial shortfalls. However, the prevalent middle provinces, cluster 2 have seen a gradual increase from 15% in adoption of IRS technology in 2021 to 60% in 2023. This trend is expected considering moderate development within western cluster and IRS, which is aimed at solving problems related to the weak levels of signal coverage within this region. In summary, the trend also places emphasis on the growing reliance on IRS in the narrowing of connectivity divides, especially where substantial population deficiencies exist.

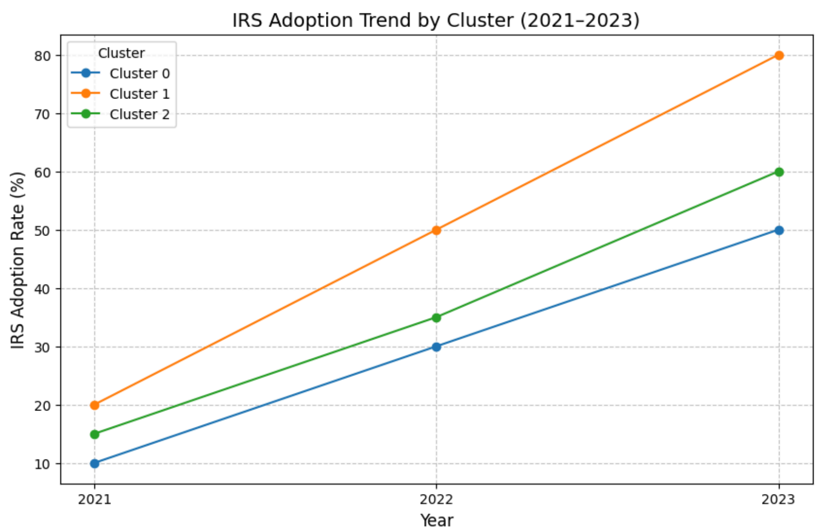

Figure 1: IRS Adoption Trend by Cluster

3.3 Signal Trends by Cluster

The undeniable performance, as well as the intervention differences, across clusters is evident with the strong signal coverage trends in the clusters. This is because a relatively strong signal mostly present in Cluster 0, where between 1400 and 1500 villages signal coverage stably possesses every year while the cluster's advancement in infrastructure presented the least need for. Cluster 1 still being underserved, managed only slight improvements where relatively lesser villages than other clusters reported strong signals, meaning effective infrastructure needs to be large.stood However, Cluster 2 showed more than a steady increase in the number of villages with strong signal coverage, indicating that the measures to enhance the transition from weak signal to strong signal prevails. There are inequalities between clusters as these trends show and emphasize the necessity of putting investments first in regions which are limited in coverage expansion.

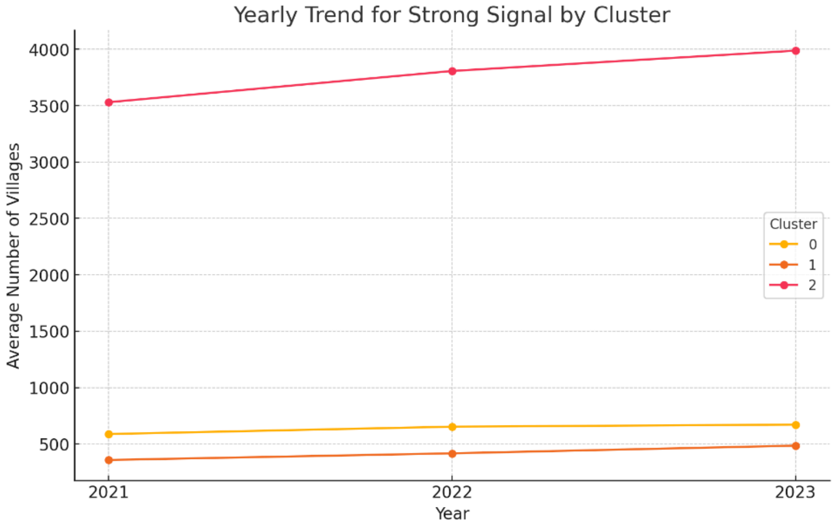

Figure 2: Yearly Trend for Strong Signal Coverage by Cluster.

Trends of the coverage in weak signals further depict the difficulties and improvements over the clusters. Cluster 0 had a weak signal coverage that was close to zero which indicates that the cluster has a well developed infrastructure. With slow gradual enhancements from IRS deployments and population of BTS, cluster 1 had high weak signal coverage, accounting for over 3000 populations per annum. On the contrary, weak signal coverage within Cluster 2 has been on a particular decline, which illustrated continued focus to augmenting the capacity of the network and minimizing the encroachment of the signals. These trends indicate that there are still problems in cluster one and some progress in cluster two illustrating the impact of the targeted interventions are not the same across clusters.

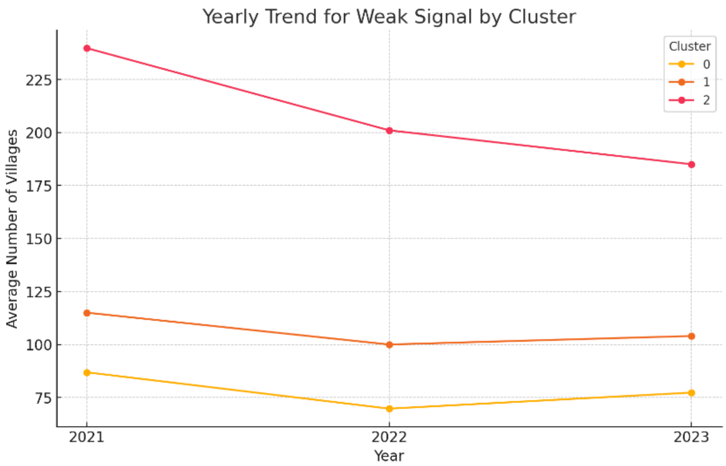

Figure 3: Yearly Trend for Weak Signal Coverage by Cluster.

The analysis of villages with no signal reveals important inequalities in access to infrastructure. Clusters in which more than ten villages lacked signal throughout the time period considered also had better infrastructure almost consistently. This is the case for Cluster 0; it averaged less than two villages without signal and had less than ten villages without signal every year, which demonstrates good telecommunication coverage. However, Cluster 1 recorded the highest number of villages without signal, averaging 50–60 each year, but slight decreases were seen with IRS and UAV-based approaches. While the no-signal areas within Cluster 2 witnessed some declines which may be attributed to attempts at extending coverage into under-connected areas, the cluster also witnessed moderate reductions. These observations highlight an urgent requirement for robust action in Cluster 1 where no-signal zones are prevalent so that communication services can reach equal levels.

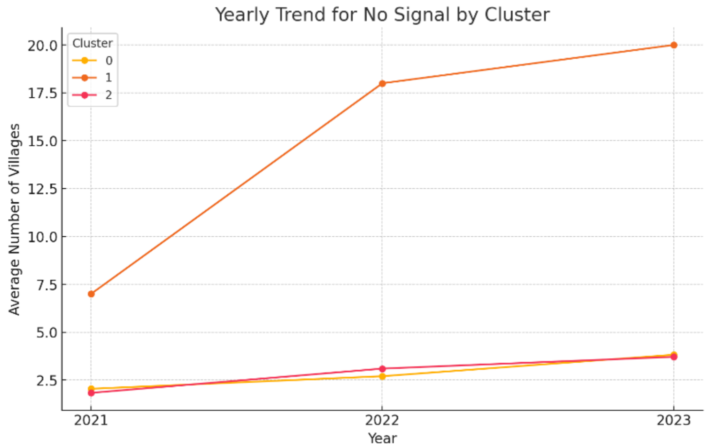

Figure 4: Yearly Trend for Villages with No Signal by Cluster.

3.4 Cluster Statistics

According to the cluster statistics for the year 2023, there are notable differences in the provision of signal coverage among the three clusters. Cluster 0, which includes high performing provinces had the greatest average number of villages equipped with strong signals that stood at 1460. This cluster however had the least amount of coverage for weak signals averaging about 120 villages and practically no villages without signals with only a village being recorded. These statistics are a reflection of the high levels of network performance and well developed infrastructure in Cluster 0.

Conversely, in considering the underserved areas, the greatest difficulties were recorded in Cluster 1. In this cluster, high signals were recorded for 3500 villages, which also had the highest average of strong signals for this cluster at 3080 and 60 without any signals. Such figures emphasize the need for integrating IRS, deploying BTS and UAVs assisted connectivity to minimize connectivity gaps and enhance network quality.

Cluster 2 where the moderately performing provinces are situated showed mixed performance. It reported a total of eight hundred (800) villages with strong signal coverage, one hundred (100) villages with weak signals and twenty (20) villages without signal strength. These statistics suggest that efforts are being made in increasing coverage and improving signal quality when compared to Cluster 1, but not everything is perfect as there is still a problem in the strength of the signals, in particular the transition from weak signals to strong signals.

Overall, the evidence suggests the different connectivity gaps and infrastructure deficiencies present within the clusters which would require more specific and contextual interventions to achieve the desired effect in addressing the digital divide. For instance, Cluster 1 has the largest investment requirements, while Clusters 0 and 2 only need maintenance and additional targeted upgrades.

Table 1: Average Villages per Signal Category by Cluster (2023)

Cluster	Strong Signal	Weak Signal	No Signal
0	1460	120	1
1	3500	3080	60
2	800	100	20

4. Discussion

4.1 Tailored Strategies by Cluster

Cluster 0 : Maintain performance, pilot 5G technologies, and automate BTS maintenance.
Cluster 1 : Deploy BTS infrastructure, expand IRS coverage, and adopt UAV-assisted connectivity.
Cluster 2 : Upgrade BTS infrastructure, deploy small cells, and utilize IRS to improve weak signals.

Table 2: Yearly Strategies by Cluster

Cluster	Year	Strategy
0	2021	Evaluate and monitor BTS infrastructure.
	2022	Pilot advanced technologies like 5G.
	2023	Automate maintenance for cost efficiency.
1	2021	Identify priority areas for BTS deployment in regions with no signal.
	2022	Expand connectivity using satellite solutions.
	2023	Upgrade weak signals to strong signals using hybrid BTS-IRS technology.
2	2021	Enhance existing BTS infrastructure capacity.
	2022	Deploy small cells to expand coverage.
	2023	Modernize BTS technology for improved efficiency.

4.2 Policy Implications

Collaborative efforts between government and private stakeholders are essential to address logistical challenges and ensure cost-effective implementation.

5. Conclusion

This work, as the analysis in this part shows, concerns the emergence of advanced telecommunication technologies like deployment of IRS, UAV-assisted connectivity, D2D communication, which can help to solve rural connectivity gaps in Indonesia. Classification of the regions into three clusters allows for more focused approaches whereby the most pressing needs are for most underserved regions, Cluster 1, moderate deployment levels in Cluster 2, and best provinces are encouraged to innovate in Cluster 0. By implementing these measures, Indonesia can close the digital divide. Indonesia can offer reliable telecommunication services to rural communities ushering in sustainable development.

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