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Optimization of Fiber to the Home Network Using a Genetic Algorithm in Medan

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ABSTRACT

Urban GPON FTTH planning must jointly manage feeder length and limited optical cores. This study develops a two-stage planning framework for a real GPON FTTH network in Medan, Indonesia. A road-constrained graph and Genetic Algorithm (GA) with a set-cover decoder are used to select and order closures; a closure-level pre-splitter power-margin rule then screens locations for splitter 1:2 deployment. This coordinated route-splitter evaluation is the study's main contribution because it links spatial routing with core-use decisions rather than treating them separately. The GA used 80 individuals, 100 generations, tournament selection, ordered crossover (0.90), and swap/segment-shuffle mutation (0.15). The resulting 7.02-km feeder covered all 29 service areas through nine closures and was 6.4% and 15.4% shorter than the two existing routes (7.50 and 8.30 km). Seven closures met the 2.45-dB pre-splitter margin rule; applying splitter 1:2 only at those locations reduced core requirements from 216 to 121 (43.98%), which fits the available 144-core feeder capacity and leaves 23 cores for expansion. The framework provides a repeatable decision-support method for urban FTTH planning; field power measurements and cost constraints should be included before construction.

Keyword: *FTTH, Genetic Algorithm, Main Feeder Routing, Power Budget, Splitter 1:2*

ABSTRAK

Perencanaan FTTH berbasis GPON di wilayah perkotaan perlu mengelola panjang *main feeder* dan keterbatasan kapasitas *core* secara bersamaan. Penelitian ini mengembangkan kerangka perencanaan dua tahap pada jaringan FTTH berbasis GPON di Kota Medan. Graf yang dibatasi jaringan jalan dan Algoritma Genetika (GA) dengan *decoder set-cover* digunakan untuk memilih serta mengurutkan *closure*, kemudian aturan *margin* daya sebelum *splitter* digunakan untuk menyeleksi lokasi penerapan *splitter* 1:2. Kontribusi utama penelitian adalah menghubungkan keputusan rute spasial dengan keputusan pemanfaatan *core*, bukan menganalisis keduanya secara terpisah. GA menggunakan 80 individu, 100 generasi, *tournament selection*, *ordered crossover* (0,90), serta mutasi *swap*/*segment-shuffle* (0,15). Jalur hasil sepanjang 7,02 km mencakup 29 area layanan melalui sembilan *closure* dan lebih pendek 6,4% serta 15,4% dibandingkan dua jalur eksisting sepanjang 7,50 km dan 8,30 km. Tujuh *closure* memenuhi aturan *margin* sebelum *splitter* sebesar 2,45 dB, penerapan *splitter* 1:2 hanya pada *closure* tersebut menurunkan kebutuhan *core* dari 216 menjadi 121 core (43,98%), sehingga berada di bawah kapasitas *main feeder* 144 *core* dan menyisakan 23 *core* untuk pengembangan. Kerangka ini menyediakan metode pendukung keputusan

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yang dapat diulang untuk perencanaan FTTH perkotaan, pengukuran daya lapangan dan batasan biaya perlu dimasukkan sebelum konstruksi.
Keyword: Algoritma Genetika, FTTH, Jalur Main Feeder, Power Budget, Splitter 1:2

1. Introduction

Fiber to the Home (FTTH) based on Gigabit-capable Passive Optical Network (GPON) is widely used for urban broadband because passive optical distribution infrastructure can deliver high bandwidth over scalable fiber access networks [1],[3]. In this architecture, the main feeder links the Optical Line Terminal (OLT) to downstream distribution points. Its route affects feeder-cable length, installation effort, optical attenuation, and the amount of fiber-core capacity reserved for current and future services [1],[3].

At the Medan case study, conventional planning produced two alternative main feeder routes of 7.50 km and 8.30 km. The planning area contains 29 service areas (A–AC) with an aggregate demand of 216 cores, whereas the available main feeder capacity is 144 cores. The practical problem is therefore not only to shorten the road-constrained route but also to use available cores more efficiently without applying splitter devices at optically unsuitable closures.

Recent PON studies have addressed topology, equipment placement, cable routing, splitter selection, and capacity decisions through exact and metaheuristic methods. Dias et al. [4] applied an evolutionary strategy to practical PON design using real maps, while Li and Shen [5] addressed multi-factor fiber-route planning. Mrabet et al. [6] used GA for next-generation PON capacity optimization. Yazar et al. [7], Kokangul and Ari [8], and Rabbani et al. [9] incorporated passive-splitter, loss, capacity, or location-allocation decisions in optical-network planning. At the FTTH planning level, Ramadonna et al. [10], Pratama et al. [11], and Padjodjang et al. [12] applied GA to route selection and checked optical feasibility through attenuation or power-budget analysis.

However, these studies do not directly resolve a main-feeder decision in which predefined service areas must first be covered along real road paths and the selected closures must then be screened for splitter 1:2 use using a consistent pre-splitter power-margin rule. Treating route selection and splitter feasibility as separate activities can produce a short route with unsuitable splitting points or a core-saving configuration that is not aligned with the selected feeder path.

This study addresses that problem through a coordinated two-stage framework. First, a Genetic Algorithm (GA) searches for a road-constrained main feeder route using a set-cover decoder that selects closures only when they add new service-area coverage. Second, a closure-level power-margin calculation determines eligibility for splitter 1:2 deployment. The study aims to (i) obtain the shortest feasible main feeder route covering all 29 service areas, (ii) identify closures eligible for splitter 1:2 deployment, and (iii) quantify route-length and core-use improvements relative to the existing designs. The contribution is a reproducible workflow that integrates routing, coverage, and splitter-screening decisions for urban GPON FTTH planning.

2. Method

This research used a quantitative, simulation-based case-study design. All network entities in the defined planning area were analyzed; therefore, no statistical sampling of customers or closures was performed. The workflow comprises input-data preparation, road-graph construction, GA optimization, and power-margin screening for splitter 1:2 deployment. Figure 1 illustrates the workflow.

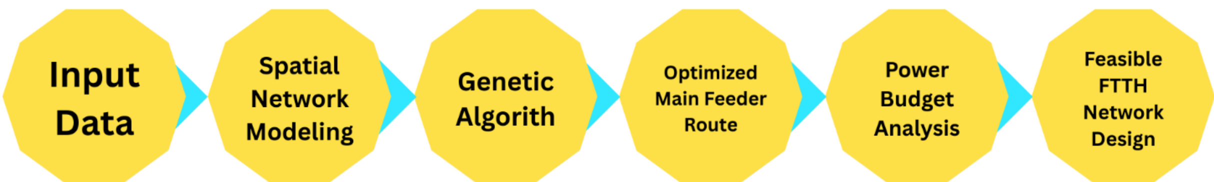

Figure 1. Research Methodology Framework

2.1. Input Data

The case dataset was compiled from company planning documents, field-verified closure coordinates, and a KML road LineString layer prepared in Google Earth Pro. It includes one OLT, 24 candidate closures, 29 service areas, and the core demand assigned to every area. The closure-area mapping was checked before optimization so that a closure could be selected only if it contributed new coverage. The 7.50-km and 8.30-km existing routes were retained only as benchmark alternatives. Table 1 summarizes the input data and model parameters.

Table 1. Input Data and Model Parameters

Component	Parameter	Value
Study data	OLT	1
Study data	Candidate closures	24
Study data	Service areas	29 (A–AC)
Study data	Total core demand	216 cores
Benchmark	Existing feeder capacity	144 cores
Benchmark	Existing routes	7.50 km; 8.30 km
GA	Population; generations	80; 100
GA	Selection	Tournament, k=3
GA	Crossover	OX, px=0.90
GA	Mutation	Swap and segment shuffle, pm=0.15
GA	Random seed	22
Power model	OLT launch power	+5.00 dBm
Power model	Fiber / connector / splice loss	0.35 dB/km; 0.25 dB; 0.10 dB
Power model	Splitter 1:2 loss	3.40 dB
Power model	Pre-splitter margin threshold	2.45 dB

2.2. Spatial Network Modeling

Spatial data were transformed into a weighted, undirected graph G=(V,E). The OLT and every candidate closure were snapped to their nearest road-graph nodes. Road segments formed the edges, and each edge weight was its physical length. Dijkstra’s algorithm was run from the OLT and each closure node to pre-compute shortest-path distances and reconstruct the corresponding road paths. The resulting route is constrained to deployable road corridors rather than Euclidean straight lines, as in practical fiber-planning approaches that use real network geography [4],[5].

Let U denote the set of 29 service areas and A(c) the areas served by candidate closure c. The decoder scans a chromosome from left to right and selects a closure only when A(c) adds at least one previously uncovered area. The scan stops once the union of selected coverage sets equals U. This set-cover step removes redundant closure visits before the route is evaluated.

2.3. Genetic Algorithm Optimization

Each chromosome is a permutation of the 24 candidate closures. The decoder generates a selected closure sequence, and the route is formed by connecting the OLT to those closures in decoded order through pre-computed shortest paths. The route length for chromosome x is calculated as:

$$L(x) = \Sigma_{\mathrm{r}}^{=0\mathrm{m}-1} d(v_{\mathrm{r}}, v_{\mathrm{r}}^{+1}) \quad (1)$$

where v_0 is the OLT, $v_1,\ldots,v_m$ are the decoded closures, and d(·) is the road-network shortest-path distance. The GA uses 80 chromosomes for 100 generations. Parents are selected by tournament selection (k=3), ordered crossover (OX) is applied with probability 0.90, and swap and segment-shuffle mutation operations are triggered with probability 0.15. The random seed is fixed at 22 to make the reported run reproducible. Permutation-based GA representations are commonly used for constrained optical-network and route-planning problems because they preserve valid visiting sequences while allowing effective exploration [4],[10],[13].

2.4. Optimized Main Feeder Route

$$f(x) = L(x) + 0.05|S(x)| + 10^9|U - C(x)| + 10^9\Sigma_{c\in S(x)} I[Mpre(c) \leq 0] \quad (2)$$

Here, S(x) is the set of decoded closures, C(x) is the resulting service-area coverage, and I(·) is an indicator function. The 0.05 term discourages unnecessary closure selections, whereas the large penalties enforce complete coverage and exclude solutions with nonpositive pre-splitter power margin. The global best solution across all generations is retained for reporting.

The output is a road-constrained route that covers every service area with the minimum fitness observed in the run. The selected closure sequence, route length, coverage status, and objective-function components are then passed to the power-margin evaluation.

2.5. Power Budget Analysis

Power-budget analysis is performed after the road route is known. For a closure at cumulative feeder distance d (km), the feeder loss and calculated pre-splitter margin are obtained from the fiber, connector, and splice losses as follows:

$$nsp(d) = 1 + \lfloor d/3 \rfloor; Lfeeder(d) = 0.35d + 2(0.25) + 0.10nsp(d) \quad (3)$$

$$Mpre(d) = 5.00 - Lfeeder(d); Mpost(d) = Mpre(d) - 3.40 \quad (4)$$

The model uses 0.35 dB/km fiber attenuation, two 0.25-dB OLT connectors, one initial 0.10-dB splice, and one additional 0.10-dB splice for each completed 3-km interval. A splitter 1:2 adds 3.40 dB. A closure is eligible for splitter deployment when its pre-splitter margin is at least 2.45 dB. The post-splitter value is retained as a diagnostic indicator. This loss-screening procedure follows the link-budget logic used in FTTH-GPON planning studies [3],[11],[12]; the GPON Class C+ reference limit is 32 dB of optical path loss [14].

2.6. Feasible FTTH Network Design

The final design combines the GA route with the closure-level splitter decision. Core demand q_i is halved when the selected closure serving area i is eligible for a splitter 1:2; otherwise q_i is retained. Each service area is counted once in the final allocation even when more than one candidate closure can cover it.

The model outputs the optimized route, selected closures, service-area coverage, pre- and post-splitter margins, splitter eligibility, and aggregate core requirement. This separation makes the routing search and the engineering screening transparent and repeatable for other network datasets.

3. Result

This section reports the results for the reproducible GA run using seed 22. The analysis presents the objective-function output, route comparison, convergence behavior, closure-level power-margin screening, and the resulting effect on fiber-core utilization.

3.1. Objective Function Evaluation and Route Length Result

The final chromosome decoded to the sequence OLT–Closure-3–Closure-9–Closure-10–Closure-12–Closure-17–Closure-19–Closure-21–Closure-23–Closure-24. These nine closures collectively covered all 29 service areas. The route length is obtained by summing the shortest-path distance of every consecutive pair in the decoded sequence, as expressed in Equation 1.

The shortest feasible route length was 7.0199 km, reported as 7.02 km. Its final fitness was 7.4699, consisting of the route length plus a 0.45 closure-count term for nine selected closures. Both the coverage and technical penalties were zero, indicating that every service area was covered and no selected closure had a nonpositive pre-splitter margin. Table 2 summarizes the final decoding and objective-function result.

Table 2. Final Decoded Route and Objective-Function Result

Metric	Result
Selected closure sequence	OLT–C3–C9–C10–C12–C17–C19–C21–C23–C24
Selected closures	9
Service-area coverage	29/29 (100%)
Route length, L(x)	7.0199 km
Final fitness, f(x)	7.4699
Coverage penalty	0

3.2. Power Margin Evaluation Before Splitter Deployment

The pre-splitter margin decreases as cumulative distance from the OLT increases because fiber and splice losses accumulate along the route. The calculated values range from 4.31 dB at Closure-3 to 1.74 dB at Closure-24. Table 3 presents the closure-level screening result. Seven closures satisfy the study-defined eligibility criterion Mpre ≥ 2.45 dB. Closure-23 and Closure-24 do not satisfy this criterion and are therefore excluded from splitter 1:2 deployment.

Table 3. Closure-Level Screening Result

Closure	Distance (km)	Mpre (dB)	Mpost (dB)	Eligible	Service areas
Closure-3	0.25	4.31	0.91	Yes	AA, AB
Closure-9	1.72	3.80	0.40	Yes	A, Z
Closure-10	1.95	3.72	0.32	Yes	B, C, Z
Closure-12	2.42	3.55	0.15	Yes	D, E, N, O, Q, R, Y
Closure-17	3.60	3.04	-0.36	Yes	D, E, F, G, H, I, J, K, L, M
Closure-19	4.07	2.88	-0.52	Yes	AC, E, N, W
Closure-21	4.81	2.62	-0.78	Yes	P, Q, S, T
Closure-23	6.00	2.20	-1.20	No	U, X
Closure-24	7.02	1.74	-1.66	No	V, X

3.3. Penalty-Based Constraint Handling Result

The final solution covered all 29 service areas; hence $|U - C(x)|=0$ and the coverage penalty was zero. All nine selected closures had a positive pre-splitter margin, so the feeder-route feasibility penalty in Equation 2 was also zero. Splitter eligibility is a separate engineering screen, requiring Mpre ⩾ 2.45 dB; therefore, Closure-23 and Closure-24 remain in the route to provide coverage but are excluded from splitter deployment. This distinction allows the GA to retain an optically feasible feeder route without forcing splitter installation at every selected closure.

The final fitness consequently reflects only route length and the small closure-count regularization. This result confirms that the reported route is not an artifact of a penalty-dominated solution

3.4. Comparison Between Existing and GA-Optimized Routes

The GA route was compared with the two existing main feeder alternatives designed through conventional planning. Relative to the 7.50-km route, the optimized route reduces the required feeder length by 0.48 km. Relative to the 8.30-km route, the reduction is 1.28 km.

The percentage reductions are 6.40% and 15.42%, respectively. These values show that the existing routes are feasible deployment alternatives but are not minimum-length solutions under the road-network and coverage model used in this study. The detailed comparison is reported in Table 4.

Table 4. Comparison of Routes

Route	Length (km)	Reduction (km)	Reduction (%)
Existing route 1	7.50	0.48	6.40
Existing route 2	8.30	1.28	15.42
GA-optimized route	7.02	–	–

3.5. Genetic Algorithm Convergence Result

The best route length decreased sharply in the early generations. A penalty-free solution with a 9.38-km route was obtained at generation 6, and the 7.02-km route length first appeared at generation 15. The best fitness improved further at generation 17 because the closure-count term favored a route with the same rounded length but fewer selected closures. The best fitness then remained 7.4699 through generation 100.

3.6. Power Budget Feasibility and Splitter 1:2 Implementation

Splitter 1:2 is deployed only at Closure-3, Closure-9, Closure-10, Closure-12, Closure-17, Closure-19, and Closure-21. These closures meet the 2.45-dB pre-splitter margin rule. Closure-23 and Closure-24 remain unsplit because their pre-splitter margins are 2.20 dB and 1.74 dB, respectively.

The post-splitter indicator becomes negative at some farther eligible closures because of the additional 3.40-dB splitter loss. In this study, that value is a planning diagnostic rather than the eligibility rule; it identifies closures that require end-to-end received-power verification before field implementation. The analysis therefore does not claim that a feeder-only calculation replaces on-site optical measurement, receiver-sensitivity verification, or OTDR testing, which are customary in FTTH feasibility assessment [1],[3],[11],[12].

3.7. Impact of Splitter 1:2 on Optical Core Utilization

Before splitter deployment, the 29 service areas require 216 cores. The seven eligible closures cover 26 areas with a combined requirement of 190 cores. Applying splitter 1:2 at those closures halves this component to 95 cores, while the three areas assigned to ineligible closures retain 26 cores.

The aggregate requirement becomes 121 cores, a reduction of 95 cores or 43.98%. Because the available feeder capacity is 144 cores, the proposed allocation leaves 23 cores for future expansion. Table 6 presents the calculation.

4. Discussion

The findings are interpreted below in relation to road-constrained PON planning, GA search behavior, optical feasibility, and practical feeder-capacity decisions. The discussion distinguishes the evidence produced by the model from issues that still require field validation.

4.1. Main Feeder Route Optimization

The route reduction is attributable to the combination of set-cover decoding and road-network shortest paths. Conventional planning can follow major roads or an intuitive center of coverage, whereas the decoder selects a closure only when it adds new service-area coverage and the GA searches the order in which those closures are visited. The result is therefore not merely a shorter geometric line; it is a shorter route after accounting for mandatory road corridors and complete service-area coverage.

This interpretation is consistent with practical PON planning studies in which topology, cable routing, splitter placement, and capacity decisions must be evaluated jointly [4],[9]. The numerical reductions should not be compared directly with percentages reported elsewhere because network size, road topology, demand distribution, and objective functions differ. Their relevance is that the GA improves both available Medan benchmarks under the same coverage requirement.

4.2. Genetic Algorithm Convergence Behavior

The convergence trace shows two phases. In the early phase, large penalty reductions dominate because the population moves from incomplete or unfavorable candidates to feasible coverage. In the later phase, the route length stabilizes and the fitness improves through closure-count regularization. The improvement from generation 15 to generation 17 illustrates why route length alone is insufficient when two routes have similar lengths but use different numbers of closure points.

Tournament selection, OX, and mutation are suitable for the permutation representation because they combine parent subsequences while preserving closure uniqueness. Comparable GA-based FTTH and PON studies also use evolutionary search to manage route, equipment, or capacity decisions under multiple constraints [4],[6],[10],[12]. Lee and Kim [13] further note that the quality of the initial population can affect convergence stability in constrained network routing. Nevertheless, the present evidence is based on one repeatable seed rather than a multi-seed statistical experiment. Future work should report mean, variance, and significance tests across independent runs before making a broad claim about GA robustness.

4.3. Power Budget Constraints and Splitter Deployment

The closure-level screening prevents core-efficiency decisions from being based on demand alone. The two farthest closures were not split because their pre-splitter margin fell below the study threshold. This is operationally important because installing splitter 1:2 at every closure would maximize nominal core reduction but would ignore the additional insertion loss that accompanies splitting.

The distinction between the pre-splitter eligibility rule and the post-splitter diagnostic must be retained when interpreting the results. The model confirms that selected splitter locations satisfy the stated planning rule and that the feeder-loss calculation is evaluated against the GPON Class C+ reference [14]. It does not replace a complete OLT-to-ONT power budget, receiver-sensitivity check, or field power-meter/OTDR measurement. Those measurements are necessary before construction, particularly at farther closures with limited post-splitter headroom [1],[3],[11],[12].

4.4. Optical Core Utilization Efficiency

The core result has direct planning value because the initial demand of 216 cores exceeds the available 144-core feeder capacity, whereas the splitter-screened configuration requires 121 cores. Rather than installing an additional feeder cable, the model creates 23 cores of headroom within the currently available capacity. This supports the PON-planning principle that capacity decisions should be integrated with topology, splitter, and equipment-selection decisions [4],[6],[9].

The result should be interpreted as a capacity-planning effect, not as a full CAPEX saving. The analysis does not include cable prices, splitter hardware, construction labor, pole availability, permits, maintenance, or service-restoration requirements. A financial conclusion therefore requires a subsequent cost model.

4.5. Practical Implications for FTTH Network Planning

For an Internet Service Provider, the framework provides a traceable sequence of decisions: map network entities to road corridors, generate a fully covered feeder route, inspect closure-level margins, and quantify the core consequence of splitter decisions. The outputs can be reviewed by planning, construction, and operations teams before a route is released for implementation.

The same workflow can be adapted to other urban areas by replacing the OLT, closure, coverage, and road-network inputs. Its practical transferability depends on the quality of spatial data and on local construction constraints. Integrating cost, resilience, end-to-end optical measurements, and repeated GA runs would turn the present single-objective planning tool into a more complete deployment decision-support system.

5. Conclusion

This study developed a coordinated GA and power-margin framework for GPON FTTH main feeder planning in Medan. The GA used road-constrained shortest paths and a set-cover decoder to produce a 7.02-km route through nine closures while covering all 29 service areas. The route is 6.40% shorter than the 7.50-km existing route and 15.42% shorter than the 8.30-km existing route.

The closure-level splitter screen identified seven closures that meet the 2.45-dB pre-splitter margin criterion. Applying splitter 1:2 only at those locations reduced the total core requirement from 216 to 121, or 43.98%, and brought the planned requirement below the available 144-core feeder capacity with 23 cores of expansion headroom.

The theoretical and practical contribution is a transparent workflow that links service-area coverage, road-based routing, and splitter-based core allocation rather than treating these decisions independently. The approach can support early-stage feeder planning, particularly when existing capacity is constrained and a full feeder replacement is undesirable.

The study is limited by its single case, fixed GA seed, feeder-only optical calculation, and exclusion of cost, civil-work, resilience, and field-measurement constraints. Future research should conduct multi-seed and multiobjective optimization, incorporate CAPEX/OPEX and resilience criteria, extend the model to sub-feeder and distribution layers, and validate candidate routes through on-site power-meter and OTDR measurements.

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