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Access-Segment Substitution in Passive Optical Networks: A Feasibility-Gated Decision Logic for RF–PON Hybrid Deployment Efficiency

MG Kasheera Gamith
IIC University of Technology

Abstract - Broadband access networks must expand under stringent cost and time constraints while meeting rising service expectations. Passive Optical Networks (PON) provide strong long-term capacity and scalability, yet real-world deployment bottlenecks persist particularly in the access (drop) segment where civil works, rights-of-way, and premises-level variability dominate rollout lead time and cost per connection. This paper reframes "hybrid access" not as a generic technology integration problem but as a segment-level substitution decision: retaining fiber in feeder and distribution segments while selectively substituting the access segment with Radio Frequency (RF) access when feasibility conditions are satisfied. We develop a feasibility-gated, decision-traceable framework that (i) decomposes the Optical Distribution Network (ODN) into feeder, distribution, and access segments; (ii) defines a feasibility gate for RF substitution across bandwidth sufficiency, service-level constraints, coverage feasibility, and reliability; and (iii) evaluates deployment efficiency through scenario-based comparative reasoning across urban high-density, suburban medium-density, and rural/low-density contexts. Findings indicate that access-segment substitution can yield material reductions in time-to-connect and/or cost-per-user where civil works dependency is binding, while advantages are moderated in dense urban environments where RF densification, coordination, and site constraints can shift the critical path. The framework contributes a managerial decision logic that connects feasibility screening, context conditions, and deployment efficiency outcomes into actionable guidance for operators and policymakers, while remaining explicit about boundary conditions and non-statistical generalization. (Cisco Systems, Inc., 2020; International Telecommunication Union [ITU], 2022; Broadband Commission, 2021; World Bank, 2020a).

Keywords - broadband deployment, PON, RF–PON hybrid, segment substitution, deployment efficiency, feasibility gate, techno-economic decision logic.

I. INTRODUCTION

Broadband connectivity has become foundational to social and economic participation, yet deployment remains constrained by time-to-connect, capital intensity, and implementation friction. While PON architectures remain the dominant fixed-access approach due to their bandwidth and lifecycle scalability, rollouts repeatedly face the same practical bottleneck: the access (drop) segment, where each premises connection entails localized permissions, physical obstacles, and civil works exposure. These constraints translate into high variability in deployment lead times and cost per connected user often overwhelming gains from declining optical equipment costs and improved upstream network designs. (ITU, 2022; Broadband Commission, 2021; World Bank, 2020a)

A growing body of work addresses "hybrid" access strategies often framed as integrating different technologies (fiber, wireless, coaxial, etc.) to achieve coverage and performance objectives. However, much of this discourse remains technology-centric (performance and architecture compatibility) rather than decision-centric (where and why substitution is justified under deployment constraints). This paper argues that a more defensible and managerially useful framing is access-segment substitution: retain fiber where aggregation economies and long-term capacity are decisive (feeder/distribution), while substituting the access segment when RF can meet feasibility conditions and materially reduce deployment friction.

Research gap and contribution

Existing hybrid access narratives often under-specify (i) minimum feasibility conditions that make RF substitution comparable to fiber access, (ii) the mechanism by which segment substitution changes the deployment critical path, and (iii) boundary conditions that limit generalization. This paper contributes:

- A segmentation-based substitution logic: positioning hybrid RF–PON as selective access-segment substitution rather than end-to-end technology replacement.
- A feasibility gate: explicit screening criteria that ensure only viable RF options enter comparative evaluation.
- A decision-traceable deployment efficiency evaluation: scenario-based comparative reasoning across representative contexts (urban/suburban/rural), linking assumptions → mechanisms → expected patterns → boundary conditions.
- Managerial guidance: a concise decision logic usable in planning and policy contexts without implying statistical inference. (Power, 2002; Simon, 1997)

Research questions

RQ1: Under what feasibility conditions can RF access credibly substitute the PON access segment without undermining broadband service deliverability?

RQ2: How does access-segment substitution change the controlling mechanism of deployment time and cost per user across deployment contexts?

RQ3: In which contexts does an RF–PON hybrid improve deployment efficiency relative to pure fiber access, and what boundary conditions moderate or reverse the advantage?

Paper structure

Section 2 positions access-segment substitution relative to hybrid access literature and deployment constraints. Section 3 presents the framework: segmentation model, feasibility gate, constructs, and propositions. Section 4 details the scenario-based method. Section 5 reports comparative outcomes. Section 6 discusses implications, boundary conditions, and limitations. Section 7 concludes.

II. BACKGROUND AND CONCEPTUAL FRAMING

Why the access segment dominates deployment constraints

PON ODN deployment can be decomposed into feeder, distribution, and access segments. Feeder and distribution segments typically benefit from aggregation economies and planned corridor construction, while the access segment must be executed at the premises level and is repeatedly exposed to idiosyncratic physical and administrative constraints. Consequently, time and cost risks are structurally concentrated in the access segment. This concentration is widely reflected in broadband policy and implementation reports that emphasize the friction of "last-mile" rollout, including civil works dependency, permitting, and coordination challenges. (ITU, 2022; Broadband Commission, 2021; World Bank, 2020a)

From "hybrid integration" to "segment substitution"

Many hybrid approaches emphasize technological integration (e.g., converging wireless and fiber for reach and capacity). In contrast, access-segment substitution is explicitly a deployment strategy: it targets the segment where constraints dominate and where substitution can reduce dependency on trenching/ROW processes. This reframing supports decision traceability: the rationale is not that RF is "better" than fiber, but that it can, under feasibility constraints, alter the controlling mechanism of deployment efficiency.

Decision support perspective

Because access deployment decisions are context-dependent, a decision-support lens is appropriate: the goal is to structure choices under constraints rather than to claim universal superiority of a technology. Decision traceability and explicit criteria improve governance and reduce bias in infrastructure planning, aligning with well-established managerial decision support foundations. (Power, 2002; Simon, 1997)

III. FRAMEWORK: FEASIBILITY-GATED ACCESS-SEGMENT SUBSTITUTION

Segment model and constructs

We define:

- Independent variable: Access implementation mode (fiber access vs RF access vs hybrid RF–PON).
- Mediators: (i) deployment time behavior (time-to-connect), (ii) cost-per-user behavior.
- Outcome: Deployment efficiency, interpreted as the combined ability to connect users quickly and cost-effectively under context constraints while maintaining broadband feasibility.

Feasibility gate for RF substitution

RF substitution enters comparison only if it satisfies minimum feasibility across four dimensions:

(F1) Bandwidth sufficiency: can support broadband-grade throughput under shared conditions.

(F2) Service-level constraints: latency/quality bounds consistent with mainstream broadband usage.

(F3) Coverage feasibility: physically and operationally feasible to cover the target area/premises set.

(F4) Reliability/assurance: can sustain service availability and manageable operational performance.

This gate prevents invalid comparisons (e.g., comparing a non-feasible RF option to fiber). It also makes boundary conditions explicit: when feasibility fails, the hybrid strategy is not considered dominant by design.

Propositions

Because this is scenario-based analytical evaluation rather than hypothesis testing, we use propositions:

P1 (Deployment time effect): RF substitution of the access segment reduces deployment time relative to fiber access where civil works/permissions are binding.

P2 (Cost-per-user effect): RF access can produce more favorable cost-per-user characteristics under high civil works intensity or low-density rollout contexts.

P3 (Deployment efficiency effect): Hybrid RF–PON architectures can improve overall deployment efficiency relative to pure fiber access in feasibility-satisfying contexts.

P4 (Context dependence): The magnitude and direction of benefits are context-dependent and may be moderated in dense urban environments.

Method: Scenario-based analytical evaluation

Design rationale

The study uses scenario-based analytical evaluation grounded in passive/secondary evidence (standards, policy reports, planning guidance, techno-economic analyses). The goal is comparative decision logic, not statistical generalization. (ITU, 2022; Broadband Commission, 2021; World Bank, 2020a)

Scenarios

We evaluate three representative contexts:

- Urban high-density: high demand, dense morphology, strong governance/coordination constraints, potential RF densification/interference management burdens.
- Suburban medium-density: mixed morphology, moderate civil works constraints, moderate ability to scale through substitution.
- Rural/low-density: long reach, high per-premises fiber cost exposure, strong potential for civil works bottleneck relief.

Evaluation rules and replicability

- Consistency: identical segment model, feasibility gate, and interpretation rules applied across scenarios; only context conditions vary.

- Inference transparency: conclusions expressed as comparative patterns bounded by feasibility and scenario assumptions.
- Outcome coding: propositions assessed as supported/refined/bounded depending on scenario outcomes.

Results: Comparative outcomes and proposition evaluation

Mechanism shift: what substitution changes

Assumption: access-segment civil works and premises variability dominate deployment critical path.

Mechanism: RF substitution replaces trenching/ROW dependency with RF site readiness, configuration, and coordination constraints.

Expected pattern: reduced time-to-connect and/or cost-per-user where civil works are binding.

Boundary condition: gains moderate where fiber drops are short, duct reuse is extensive, or RF densification/interference coordination becomes dominant.

P1: Deployment time effect

Across suburban and rural contexts, RF substitution is expected to reduce time-to-connect primarily by avoiding trenching/permits and reducing repeated premises-level civil interventions. In dense urban settings, the advantage is moderated where RF site acquisition and coordination requirements shift the critical path. This supports P1 in a context-conditional form. (ITU, 2022; Broadband Commission, 2021)

P2: Cost-per-user effect

Cost-per-user is governed by whether costs scale with per-meter civil works (fiber access) versus equipment/site/operations (RF substitution). In rural/low-density and high-constraint contexts, RF substitution can reduce cost exposure by reducing civil works intensity. In dense urban contexts, densification and operational overhead can offset these gains, refining P2 into a boundary-aware proposition. (World Bank, 2020a; ITU, 2022)

P3: Deployment efficiency effect

Hybrid RF–PON can improve deployment efficiency by combining fiber's upstream capacity advantages with access-segment substitution where feasibility holds. However, the hybrid strategy is not universally dominant: feasibility failure or strong urban densification constraints can weaken advantage. This supports P3 in a bounded form. (ITU, 2022)

P4: Context dependence

Across all results, context conditions determine whether substitution yields improvement or simply shifts constraints. This supports P4 and reinforces the need for feasibility gating and decision traceability.

Discussion and implications

Theoretical implications

This paper's primary conceptual contribution is reframing hybrid access as segment-level substitution. The framework improves conceptual clarity: substitution targets the segment where constraints dominate rather than treating access technology choice as a uniform, end-to-end decision. This supports a more mechanism-led understanding of deployment efficiency: outcomes are governed by constraint concentration and critical path drivers, not raw link capacity alone. (ITU, 2022)

Managerial and policy implications

For operators, the framework offers a disciplined approach to evaluate when RF substitution reduces rollout risk and accelerates service activation. For policymakers, it clarifies that "faster broadband" is often a deployment governance and civil works problem as much as a technology problem, motivating interventions that reduce permitting friction and support context-appropriate deployment pathways. (Broadband Commission, 2021; World Bank, 2020a)

A practical decision lens can be expressed through criteria such as time-to-connect priority, CAPEX constraint severity, right-of-way friction, demand density, service assurance requirements, and lifecycle operational complexity consistent with multi-criteria decision support principles. (Belton & Stewart, 2002; Keeney & Raiffa, 1993)

Boundary conditions and limitations

The study is analytical and scenario-based; it does not claim statistical generalization. Conclusions transfer where feasibility conditions and scenario assumptions are comparable. Field trials could calibrate feasibility thresholds and quantify effect magnitudes. (ITU, 2022)

IV. CONCLUSION

This paper advances a feasibility-gated, decision-traceable framework for access-segment substitution in PON deployments. By isolating the access segment as the dominant locus of time and cost constraints and treating RF–PON hybridization as a substitution decision rather than generic integration, the framework offers a defensible mechanism explanation and actionable guidance. Results support the expectation that RF substitution can improve deployment efficiency in civil-works-constrained suburban and rural contexts when feasibility holds, while highlighting boundary conditions that moderate benefits in dense urban environments. The contribution is a structured decision logic that can be used in planning and policy contexts to evaluate hybrid access strategies transparently and consistently.

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