Extending Broadband past the Urban Fringe with Wireless Mesh

A Strategic Analysis with Policy Implications for Kenya's Universal Service Fund

by

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B. S. Engineering Sciences
Harvard University, 2004

SUBMITTED TO THE ENGINEERING SYSTEMS DIVISION IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEPTEMBER 2011

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ABSTRACT

As the competitive wholesale cost of bandwidth continues to plummet in Kenya, last-mile networks have become a bottleneck in the extension of affordable broadband outside major cities. In this work we explore the business case for small-scale wireless mesh networks as a means to implement demand-driven, bottom-up growth of broadband infrastructure on the outskirts of Nairobi, Kenya. Under the hypothesis that current conditions are not attractive to small scale operators (SSO), we develop a continuous growth model to understand the investment required by a SSO before a small-scale network is able to grow sustainably. The model is then used to test the effects of a variety of policy interventions on the SSO's required investment. Our analysis reveals that the two primary barriers for SSOs are license fees and inability to access market prices for upstream inputs at prices competitive with large commercial operators. Based on these results we propose government support for a SSO cooperative as an efficient method of supporting small-scale wireless networks and their operators.

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ACKNOWLEDGEMENTS

Thanks to Paul English, for all of his support and enthusiasm; to Amy Sun, for never letting me do anything halfway; to the Fabfi Wireless team, for their hours on rooftops; and to Frank Field, for bringing order to chaos.

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DEFINITIONS AND ABBREVIATIONS

AP – Access Point

APR – Annual Percentage Rate

AS – Autonomous System, referring to the organizational unit in global internet routing

CCK – Communications Commission of Kenya

CCR – Call completion rate

CSMA/CA – Carrier Sense Multiple Access with Collision Avoidance. This is the standard media access control protocol for 802.11b/g/n

CWC – Community Wireless Collective

CWN – Community Wireless Network, referring to a bottom-up broadband infrastructure built and operated by an individual or small group connected to the community the network is built in. The "community" label in this context is meant as contrast to large-scale commercial ISPs. It is not meant to imply direct ownership in the way that a municipal network would be owned by a municipality.

DIY – Do-it-yourself

DSTI/ICCP – Directorate for Science, Technology and Industry / Committee for Information, Computer and Communications Policy. This is a subunit with OECD.

ICT – Information and Communication Technology, referring broadly to telephony, networking, data services and computing.

ISP – Internet Service Provider, referring to an entity that provides internet access to the public [for a fee]. It is not meant to exclude vertically integrated companies that both operate infrastructure in addition to providing direct-to-consumer service.

KENET – Kenya Educational Network, referring to Kenya's research and education AS.

KICTB – Kenya ICT Board

KIXP – Kenya Internet Exchange Point

KPCL – Kenya Power and Light Company

LOS – Line-of-Sight

FCC – Federal Communications Commission

FOSS – Free and Open-Source Software

Goodput - A networking term referring to the application-level data throughput over a communication link. See footnote 49 for more details.

NGN – Next generation Network, referring to fiber optics and advanced wireless communications including WiFi and mobile broadband (particularly when implemented with small installations such as femtocells)

OECD- Organization for Economic Cooperation and Development

POE – Power Over Ethernet

POP – Point of Presence

PtMP – Point to Multi-Point, referring to wireless communications where multiple clients communicate with a single access point

PtP – Point to Point, referring to wireless communications where two wireless devices take directly with each other in a 1:1 configuration.

PTP – Peer to Peer, referring to file sharing on the internet

SSO – Small Scale Operator

Take Rate – The penetration of a fixed-line data service defined as the ratio of active subscribers to the number of potential customers reached by the infrastructure.

UAS – Universal Access and Service

USF – Universal Service Fund

WISP – Wireless internet service provider. This term generally refers to ISPs who provide internet service using unlicensed wireless technology such as WiFi.

INTRODUCTION

As the competitive wholesale cost of bandwidth continues to plummet in Kenya, last-mile networks have replaced international connectivity as the bottleneck in the extension of affordable broadband outside major cities. Incumbent providers have been conservative in expanding fixed-access services to any but the most profitable areas. As a result, many potential broadband customers are restricted to costly and low-performing mobile data access[1].

After investing in domestic broadband core capacity[2] to distribute bandwidth provided by undersea fiber from TEAMs, Seacom and EASSy, a looming policy question for the Kenyan government is how to expand affordable broadband access. Since the arrival of the first subsea links in 2009, regulators have been dissatisfied both with the market's ability to pass savings to consumers and the speed at which new areas were receiving broadband coverage[3]. These complaints come against a sharply divided market. For those living in wealthier residential developments surrounding the Nairobi's urban core such as Kileshewa, Lavington and Kilimani, high-performance broadband services are available (via fiber) at very competitive prices. Outside of these areas, prices begin to rise sharply as speeds drop, quickly becoming more than three times more expensive with lower performance (Murphy et al. 2010). Without a doubt, the demand for affordable, fast internet extends beyond the current reach of the infrastructure that provides it. In the current environment, the consumer is faced with the choice of paying higher prices or waiting, perhaps for years, for improved services to arrive.

Traditionally, solutions to the problem of un-serviced demand come in the form of incentives for commercial operators to build infrastructure. This approach has a variety of limitations from slow, coarse-grained demand response to the application of inappropriate and excessively expensive solutions[4].

In this work we explore the notion of empowering consumers to build broadband connectivity in response to their own demand. Having seen numerous examples of

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[1] These assertions were recently confirmed by CCK's *Study On Access Gaps in Kenya*. See Appendix D for more about broadband services and use in Kenya and references to the access gap study.

[2] Since 2004, GoK has been implementing a National Fiber Optic Network (NOFBI). As of today, 31 of 47 county centers have access to fiber connectivity either through NOFBI or through private operators (Apoyo Consultoria 2011, pp.120–126).

[3] Sentiments expressed by Kenya's ICT Secretary, Bitange Ndemo, in my interview with him, August 2010.

[4] See Background, sections 2.31 and 2.3.2, for more detail.

broadband infrastructure being constructed with inexpensive WiFi hardware for the last decade[5], we ask the question: "Is there an economically viable case for bottom-up infrastructure construction in response to a small amount of user demand?" That is, can we make a viable business case for a network of 100, 10, even 1 subscribers spread out over a large geographic area? If not, what are the barriers and how can Kenya's Universal Access initiative be leveraged to break them down?

CONCEPT: WIRELESS MESH PAST THE URBAN FRINGE

The project that generated the bottom-up network deployment concept explored in this paper began in the spring of 2010. At that time I was approached by a Boston area entrepreneur and philanthropist interested in a small-scale entrepreneurial model for expanding broadband access in Africa. The underlying working hypothesis was fairly simple: If there is a profitable, accessible business model for individuals to build broadband infrastructure, access will expand more rapidly and with more complete coverage than if only a handful of commercial telecom companies are responsible for expanding networks. Fundamentally, this is a notion that I believe in, and one that I deemed worthy of exploration.

In the summer of 2010 I travelled to Nairobi to work with a team of Kenyan university students with whom I would explore the business case for building bottom-up broadband infrastructure with wireless mesh[6]

Upon arriving in Kenya I learned about the broadband service landscape in the Nairobi area from my Kenyan collaborators who provided their "street" knowledge about what sorts of services were available[7]. The major deficiency they identified was the rapid increase in price and decrease in quality of internet services that occurred as one travelled beyond outside wealthy areas near the city center. Within only a few kilometers, the best available service would go from fiber-optic broadband, at prices comparable to what one might pay for a service like Verison's FiOS in the US, to mobile

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[5] For example, WISPA, the association for Wireless ISPs has over 350 operator-members (http://www.wispa.org).

[6] Since 2008 I have been a core contributor to the Fabfi Wireless Project (http://Fabfi.fabfolk.org). This project is focused on creating an operational model and technology platform to enable viral growth of broadband infrastructure in developing markets.

[7] See Appendix D for more detail on broadband Access and Use in Kenya.

data services that charge a minimum of $0.005/MB[8] and provide speeds in the range of 256kbps. Exploring some of these under-served areas and conducting informal interviews revealed that there was a demand for broadband service.

In addition to our own observations, Dr. Meoli Kashorda, director of the Kenya Education Network (KENET), shared his industry wisdom regarding the broadband environment in the Nairobi area[9]. In his experience, he said, "fiber [backhaul] follows the mobile operators. If the mobile companies have decided to invest in an area, you will find fiber, otherwise you will not." Paraphrasing the rest of the conversation, he described the typical data infrastructure growth model as one where mobile operators lead core infrastructure growth, selling surplus capacity to other providers as leased lines. The broad reach of mobile operators, he said, makes data transit to most places available in a macro-sense, however spanning the last mile from the POP to the customer is typically an expensive challenge.

Dr. Kashorda's assessment paralleled what we were seeing on the ground with respect to fixed-access[10] broadband services. Inside Nairobi, a variety of services were available. In large, affluent outlying communities, innovative providers such as the Wananchi Group took advantage of fiber access on existing towers to provide fixed-wireless services with WiMax in the last-mile. After this, all services other than mobile quickly tapered off.

Fiber-connected mobile towers provided an interesting opportunity for Small Scale Operators (SSOs). From a height of a typical mobile tower, a SSO could make wireless connections to sites as far as 20km away with little or no tower equipment on the remote end. This capability would allow SSOs to reach under-served areas with high-capacity backhaul connections at low cost. We resolved to explore this opportunity as part of a business model where wireless links from mobile towers were used to feed local mesh access networks in under-served areas.

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[8] This may not seem like a high price, but the price comes with two considerations. First, always-on internet consumes a lot of data. Users in our Mt. View Pilot (discussed in the following section) have been seen consuming up to 10GB/Month. Tracking my own use, I find I personally consume nearly triple this amount (without any P2P). Second, the price charged for mobile internet with Safaricom, the dominant provider, is based on the amount of data purchased in a "bundle". Those purchasing the largest bundles ($120 or more at a time) receive the $0.005/MB rate, but those purchasing smaller bundles could pay more than $0.04/MB.

[9] As some background: KENET is Kenya's research and education AS and has a mandate to provide internet capacity to institutions of higher learning nationwide. To accomplish this mission they purchase international data transit directly from undersea cables in Mombasa and build or lease domestic transit and last-mile capacity through various means to serve member universities.

[10] The term fixed-access is meant to include fixed-line and fixed-wireless services, explicitly excluding mobile wireless.

PILOTS: MT. VIEW / KANGEMI, NJABINI

Having identified what we believed to be a viable concept for expanding the reach of inexpensive broadband, we initiated a pilot project to build a qualitative understanding of its feasibility. Bottom-up broadband deployment is a very different undertaking than its top-down commercial counterpart. While a commercial network takes expertise for granted, performs extensive site surveys and purchases rights of way, the bottom-up network can begin with little knowledge or experience, follows a dynamic growth path and may finance its footprint through social currency more often than cash.

The objective of the pilot project was to observe how a bottom-up network would develop: What level of cooperation could we expect from local residents? How quickly could the Kenyan students become proficient installers and operators? Would there be sufficient demand? How much were users willing to pay? Was there a strong preference toward WiFi over mobile for data services?

Two pilot sites were selected for exploration of the CWN model. The primary site, Mt. View / Kangemi, located in the urban-fringe area of Nairobi, was selected for its mixed demographic character. The site consisted of a more affluent central section with surrounding lower-income residences. Located roughly 10km from the city center, residents had only mobile data services previous to our project. The secondary pilot site was located in the rural community of Njabini. This site had very limited data connectivity, and a low level of computer ownership[11].

The primary pilot site was designed to be an accurate approximation of the proposed CWN business model, while the second was an extreme case designed to test whether or not a non-technical operator could run a mesh network with only peer support (from the Kenyan students).

Over the course of fall 2010 and into winter 2011, I personally supported the Nairobi students in learning to build and operate a wireless mesh network based on the Fabfi[12] platform in Mt. View. The network architecture and wireless hardware is similar to that described in the Model Parameters, section (3.2). While outsiders like myself provided knowledge support, the pilot operated on a "Kenyan hands only" basis, with the local students taking the lead in the deployment and operation of the network. The Kenyans

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[11] Few individuals in Njabini owned computers, however computers are used in most of the institutions in the area, including the heath center, multiple schools, and an orphanage.

[12] http://fabfi.fabfolk.com

built relationships with community members and were able to site mesh nodes on both private residences and the buildings of local organizations.

Over the course of the nine months, the team progressively built out a network at the primary pilot site by jumping subscriber-to-subscriber with new node installations. As of last count, the network had expanded to a size of about 10 nodes, which provides wireless coverage to roughly 20 households[13].

Qualitatively, we found demand to be very high for the service[14]. 512kbps connections for about $24 per month were most popular. A smaller number of 1Mbps subscriptions were also sold for $48. Multiple customers expressed a distinct preference for the WiFi service over a mobile connection, stating the "3G was expensive" or that they disliked having to use the USB modem. We also found subscribers universally willing to allow mounting of mesh nodes at their residences and willing to pay for powering devices, despite understanding that the service was wireless and could be received from a neighboring home. The team was never denied site access and was never required to pay site rental or electricity costs.

In parallel with the Mt. View deployment, the Kenyan student team provided support to a Njabini resident in the maintenance of a three node network serving an orphanage, a clothing business and a cyber café. Because the Njabini network was more than an hour by bus from Nairobi, much of this support was performed remotely. Over the course of the pilot project the Kenyan student team successfully supported the Njabini operator who, at the time of this writing, is still operating the network. This was encouraging support for the idea that operators could successfully learn from each other, even if separated by only a few months experience.

The experience of the Mt. View pilot convinced us that the community scale WiFi was feasible in the area surrounding Nairobi; however its success depended on outside capital and operational support, such as zero-cost wireless hardware and donated bandwidth that does not scale to broad implementation. This fact motivated us to determine of what conditions must exist for such a network to arise spontaneously and survive as a broadband expansion solution.

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[13] As of March. 2011 approximately 20 paying monthly subscribers were using the service; however, the bandwidth donated by our ISP partner was insufficient to support additional enrollment (new users were put on a waiting list).

[14] After curbing enrollment due to uplink capacity constraints, the Nairobi team began generating a waiting list of future subscribers.

PROBLEM: INFRASTRUCTURE EXPANSION (IN A COMPETITIVE MARKET)

> *"In the case of fibre technologies, risks for private investment—caused by high capital expenditure in conjunction with demand uncertainty—can lead to a situation in which markets fail to efficiently provide society with fibre infrastructure."* (Sadowski et al. 2009)

In recent decades, widespread acknowledgement of the pitfalls of tightly regulated—particularly monopoly—telecommunications markets has begun a global trend toward deregulation and technological neutrality. Kenya, for one, has fully embraced this trend. While there is clear evidence that that the introduction of market competition has benefits across nearly every metric of price and quality (OECD 1995a, pp.15–18), it has the unfortunate side effect of making it more difficult to stimulate infrastructure growth on the margin.

In the last mile, the economics of competitive service provision tend to create conservatism in infrastructure expansion. Carrier-class fixed-access services are very sensitive to take rates, making competition for market share and/or protecting against competitive entry very important. Sadowski illustrates that with fiber, for example, the take rates required for profitability ensure a that market structure with more than two providers would rarely develop (2009). Others have suggested take rate requirements of roughly 50%, making competition barely, if at all, sustainable (DSTI/ICCP 2008).

With the above in mind, one might expect one of two competitive strategies:

- ***A)*** Providers compete fiercely with each other for market share in the same local markets, while making very conservative investments in new development, or
- ***B)*** First movers create natural monopolies in their own local markets by exploiting high take rates to price out competitive entry

In Kenya, prices for fiber internet seem to indicate the latter of these two is dominant. In either case, operators that impose cross-subsidies (in this case to fund speculative growth) on their customers can be undercut by competitive providers, making aggressive development of new sites a risky proposition (Nuechterlein & Weiser 2005, pp.52–55). Especially in a Kenya, where rapid drops in prices have resulted in rapid demand growth, the market is left with a significant amount of un-serviced demand[15].

SOLUTION: EVOLVING APPROACHES TO EXPANSION INCENTIVES

Based on the dynamics described in the previous section (2.3.1), it is generally agreed that the conditions of competitive, converged telecommunications create a need for exogenous or redistributive compensation to stimulate growth (OECD 1995b, p.59)

ITU's best practices suggest the implementation of a Universal Service Fund to finance competitively bid, "smart" subsidies for operators to expand infrastructure into targeted areas. In its recent report on ICT Access Gaps (Apoyo Consultoria 2011), CCK recommends closely following the Universal Service Fund model[16]. This approach has been demonstrated to be effective at generating growth with lower subsidies than previous approaches, but its top-down character makes it prone to a number of pitfalls:

- Subsidy process moves too slowly for a changing market
- Not truly technology neutral (site definition may artificially advantage one technology)
- Identifying sites can be costly and areas are bound to be overlooked
- Plays to commercial operators with credibility and experience bidding contracts
- Benefits are site-specific, but do not necessarily accrue to the locality served

While these pitfalls were perhaps acceptable in an era where broadband performance required expensive enterprise systems and economies of scale, this requirement is rapidly falling away:

> *The introduction of NGN-related technologies, such as Broadband Wireless Access (BWA) and Wi-Fi, has substantially reduced economies of scale in both the infrastructure and service segments. This has opened up the field to a wider range of small or local providers to expand universal access from a bottom-up, demand-driven approach.*

(Blackman & Srivastava 2011, pp.160–166)

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[15] While numbers are not available for un-serviced demand, the increase in internet subscriptions of 71.8% in the last fiscal year (CCK 2011d) combined with the positive response to our Mt. View pilot network and the fact that only 28% of the population has broadband access (Apoyo Consultoria 2011, p.39) suggest this is the case.

[16] See Appendix F for more on Universal Service Funds and Kenya's approach the broadband access gap.

A truly demand-driven approach to network expansion would do away with the need for subsidies to large telecoms; as such entities would never again need to expand into an untested market. Instead, large telecoms would be backfillers, expanding high-performance services into known, existing demand[17]. But I digress...

Because the bottom-up approach can be fundamentally different from the top-down approach in its capital inputs, expansion strategy, organizational structure and market position, the types of incentives needed to facilitate bottom-up growth are likely very different than the best practices described above. As I will argue later, the incentives that target the bottom-up approach pose less risk of distorting the overall market and allow better demand response.

TECHNOLOGY: UNLICENSED-BAND WIRELESS MESH

In 2002, MIT's roofnet project made headlines by deploying a fast, reliable mesh-wireless broadband network in the neighborhoods surrounding the Institute. At the time, large-scale WiFi-based infrastructure was rare at best. Routing protocols were primitive and a simple mesh node cost nearly $700 (Guizzo 2003). Since that time, numerous academics, hobbyists and commercial companies alike have been improving on the basic mesh idea with both hardware and software. Today one could deploy the same network with more than ten times the performance at one-fifth the cost.

WiFi networks are now commonly used niche solutions to gaps in carrier-class coverage and workarounds to overpriced commercial data services. In the US, the Wireless ISP Association has over 350 operator-members[18] and examples of WiFi networks providing affordable internet in places where traditional infrastructure is too costly can be found worldwide. Commodity WiFi hardware is both high performance[19] and reliable. In my own work on the Fabfi Wireless Project[20] I have seen these devices baked in the sun, drowned in water, blasted with sand at 100Mph and subjected to all manner of input power abominations with only a handful of failures.

Thanks to robust support from the open source software community, wireless routers running embedded Linux are able to perform all the basic functions of enterprise networks with no software licensing costs or support contracts. In most places, WiFi

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[17] Those familiar with the field of real-options may appreciate that the potential reduction of uncertainty for the enterprise provider making a large capital investment is desirable.

[18] http://www.wispa.org

[19] Inexpensive WiFi devices such as those used in our network can achieve up to 100Mbps goodput

[20] http://fabfi.fabfolk.com

networks also have the advantage of being free from spectrum licensing, which both decreases cost and allows for rapid deployment.

In addition to the low cost of hardware, the nature of the meshed architecture has important advantages. Critically, the maximum cost to connect any new user, provided he is within radio earshot of another user, is typically no more than the cost of a single mesh node. This feature allows the mesh to provide coverage at extremely low user densities with worst-case linear cost in the number of users.

With all these features combined, wireless mesh networks make an attractive technology for bottom-up infrastructure development. Wireless mesh will be the focus technology for this analysis.

METHODOLOGY

As explained in the Introduction (2), the following pages revolve around a simple question:

"What policy interventions are necessary to stimulate spontaneous demand-driven growth of small-scale wireless ISPs (CWNs)?"

The matter of stimulating spontaneous bottom-up growth of CWNs is an issue of creating conditions under which the CWN business case is profitable and accessible for the local operator. Based on the current lack of bottom-up infrastructure construction in the Nairobi area, we surmise these conditions do not currently exist.

The lack of attractiveness in the business case could be a function of a variety of factors: Perhaps regulatory barriers to entry are too high; perhaps the scale at which WISPs become profitable is beyond the capital access means of the target entrepreneurs; perhaps the knowledge required to build such a system is not readily available. Any one of these, or a variety of other factors could be at play. The challenge of the policymaker is to build an understanding of the factors at play and design an intervention that shifts their balance toward sustainability while minimally distorting the market.

To make an analogy, one can think of good and bad policy like methods of dismantling a bridge. At one extreme, packing the entire frame with dynamite and blowing it up will surely take the bridge down, but the shrapnel might destroy half the surrounding buildings in the process. In the other extreme, one might try to dismantle the bridge one beam at a time. Doing so would be careful and controlled, but might take years to complete with thousands of hours of labor. A third option, if one understands how the bridge is engineered, is to detonate a shaped charge on the primary weight-bearing member, severing the beam and dropping the whole bridge safely in place.

Similarly for the CWN, we want to identify policy interventions that surgically dismantle the obstacles to spontaneous, demand-driven CWN growth without unnecessary cost or complexity (provided that these interventions exist).

MODEL DESIGN

A simple illustrative model is often the best approach to viewing the impacts of various policy choices. For maximum clarity, such a model should have the feature where the inputs can be directly mapped to policy choices and the outputs directly map to desired outcomes.

DESIGN CONCEPT

The objective in building the model is to create a tool for assessing the viability of the policy objective under different market conditions, beginning with the prevailing conditions, and subsequently moving to conditions as might exist under different policy regimes. To recall our objective, we would like to enable spontaneous, demand-driven expansion of broadband infrastructure through CWNs.

From the perspective of the broadband ecosystem, the greatest differentiator for the CWN is the potential for demand-driven growth. In other words, the CWN's primary value to the market is the feature of being sustainably and *directly* deployable by a community desiring broadband service[21]. A necessary condition for demand-driven growth is that the CWN business must be attractive[22] to the SSO at the scale of existing demand in under-served areas. Implicit to this statement is the fact that demand in under-served areas is likely to be smaller or more widely dispersed than in areas served by large commercial operators. The CWN business case must, therefore, be attractive at these smaller levels of demand. In the ideal case, the CWN would be profitable for any non-zero number of potential users. This would be an ***ideal demand-driven service***. The closer the CWN approximates an ideal demand-driven service, the lower the barrier to entry for the SSO[23], and the more differentiated a benefit the CWN model provides to the overall broadband market.

In addition to the concept of being able to respond to arbitrarily small levels of demand, the optimal demand-driven service should exhibit an "instantaneous" response to

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[21] We might imagine the CWN as a community institution or an entrepreneurial venture by a community member.

[22] Attractiveness is a combination of profitability and a level of required financial risk that would be acceptable to the SSO. Specific conditions for a network to be considered attractive are discussed in Assessing Outcomes, section (3.1.3).

[23] One might imagine that the necessity of enlisting a dozen geographically co-located neighbors to commit what might be as much as 5% of their income to purchasing a service is a lot harder than enlisting only one or two in the same area.

additional demand. Obviously, in the world of physical reality nothing is truly instantaneous, but in a real sense, the SSO should be able to respond to requests for coverage from new customers without long time delays (presumably from waiting to accumulate the resources to afford network expansion). To make this idea more concrete, let's work through a simple example:

Let's assume the SSO lives in a large community with a relatively low level of demand. For concreteness, this area is village with area $4km^2$ and a density of potential subscribers such that a node with a coverage radius of 50m is unlikely to reach more than one subscriber. In this case, the SSO could deploy hundreds of nodes[24] before covering the entire area, but has to deploy one node for each new subscriber.

For round numbers, assume a new network node costs $400, and each customer connecting to this node pays $40/mo. for broadband service. Let's assume the SSO starts with $400 in his pocket, spends it on this first node and signs up one subscriber. If he makes 50% net income ($20/mo.) after expenses it will be 20 months before he can afford another node from his own free cash flow. Once he installs this new node and signs up a new customer he will have the cash to buy a third node in an additional 10 months. It will be 87 months before the SSO can install new nodes from revenue at a rate of 2/mo (40 nodes are required to generate the $800 required to install two new nodes in a single month)[25]. While the SSO operates his existing nodes to generate cash, the other users in the village are waiting for coverage. Ideally, we would want the SSO to expand to new users as quickly as he is physically able without financial constraint.

Given that free cash flow from the subscribers at any given node is unlikely to pay for the cost of the hardware in a single month, there will always be some ratio of existing:new nodes greater than 1 that must be satisfied for the operator to grow at a particular rate. Below this ratio, the operator must incur debt to make up the difference.

Taking the same numbers above, let's assume the SSO takes out loans to grow at his operational capacity at the rate of 2 nodes per month until his revenue covers both his growth and the cost of his accumulated debt[26]. In this case the SSO is able to support continuous growth from revenue in slightly less than 24 Months (this corresponds to a

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[24] About 300 nodes would cover the entire area if deployed uniformly.

[25] A table providing the calculations for the above example and the contrasting example that follows can be found in Appendix G.

[26] The example assumes that the growth rate is conservative enough with respect to the expected demand that new customers are always available. Based on the experience of the two Kenyan Pilots discussed in 2.2, we believe the chosen growth rate of 2 nodes/mo. fits this criterion in our area of interest.

scale of 47 nodes[27]); however, the SSO has now accrued nearly $9800 in debt that must then be paid down. At this point, the SSO can choose to either roll all of his free cash flow into paying down the accumulated debt, or invest some of the additional cash in increasing his peak expansion rate (potentially through hiring an apprentice or outsourcing some tasks). If the SSO simply continues to grow at the same rate, he recovers this debt in about 44 months, at which point he is already serving more than twice the number of users than he would have at the end of seven years if he grew only from free cash flow[28].

When assessing the CWN as an alternative infrastructure provider, it is this second (continuous growth) approach that we want to enable. The primary reason for approaching the CWN from the perspective of an enforced growth rate is normative. Our policy objective is rapid, sustainable growth of broadband infrastructure. Given that the competitiveness of the SSO depends largely on scale[29], it is important that individual SSOs grow quickly. Relatedly, we want the SSO to benefit from dedicating sustained effort to network growth. Also, the approach of enforcing a continuous rae of growth and identifying the point where that growth can be sustained directly addresses how quickly the CWN can afford to grow as a company (such as hiring additional labor). This is important for its long-term health and scaling[30].

To analyze the linear growth case as described above, I create a model that calculates the revenues and costs over time for the SSO. The model ***enforces*** the criterion of continuous network growth at the operational capacity of an individual operator, assuming that the operator goes into debt for any negative cash flows. The sustainable fulfillment of the continuous growth criteria satisfies our policy objective (as we will see, the criterion is un-sustainable in the base case). We will then progressively apply policy interventions to affect the model inputs and reverse-engineer a sustainable set of initial conditions. A discussion of the meaning of sustainability in this context will follow in the Assessing Outcomes section (3.1.3).

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[27] The larger scale at equilibrium is due to the cost of the incurred debt, which we assume charges interest at a rate of 20%.

[28] In the complete model the SSO also realizes other benefits from scale such as more efficient bandwidth sharing and spreading of static costs over a larger subscriber base.

[29] For instance, 10 SSOs with their own individual uplinks and single hotspots would be much less financially viable than 1 SSO with 10 network nodes served by a single uplink.

[30] As one might imagine, the operational burden of the network increases with size. An individual may be able to support 50, or maybe even 100 nodes but eventually, he or she will require assistance. In a network that is not growing sustainably, the operator lacks the resources to obtain such assistance.

MODEL MECHANICS

An iterative model is used to analyze the CWN, focusing on a single operator. The model iterates through incremental expansions of the SSO's mesh infrastructure based on a predefined node installation rate. At each step, the model calculates costs and revenues based on input variables (scaled accordingly for the size of the time step).

For instance, if an operator is assumed to install two nodes per month, the model would make in iterative step once approximately every two weeks. At the outset, the operator is assumed to have invested in a program of training and the cost of a single mesh node with an attached backhaul link[31]. At each following step, the model adds a new node and its associated cost. Adding a new node increases the maintenance cost of the network, which is a calculated as a percentage of the total capital cost of equipment, but also increases the coverage of the network. Increased coverage, combined with any applied demand growth, increases the number of subscribers. Increasing the number of subscribers increases revenues from installation and subscription fees; however, serving each subscriber comes with an associated cost related to the amount of bandwidth they consume[32].

At the end of each time step, costs and revenues are summed (including borrowing costs), adding the gain or loss to a running total. The total from time *t-1* (if negative) is used to determine the borrowing costs at time *t*. Necessarily, the model makes a simplifying assumption that increments of credit can be arbitrarily small and obtained on-demand. For short term credit (<30 days), this is true[33], but in general the simplification is likely to underestimate borrowing costs by a small amount.

The model accounts for the following costs[34]:

- Operator training
- Hardware for new nodes
- Maintenance for the existing system (assumed to be 2% of total CAPEX annually)
- Cost of uplink bandwidth
- Lease fees for commercial tower space
- Licensing fees
- Interest expenses

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[31] See Mesh Infrastructure, section 3.2.1, for more information on nodes and backhaul links.

[32] Described in Bandwidth Dimensioning, section 3.2.2.

[33] Safraricom's M-Pesa provides 30day loans of up to $60 for a premium of 10% with a 3% late payment fee: http://www.safaricom.co.ke/index.php?id=263

[34] Each of the costs will be discussed in Model Parameters, section 3.2, and a summary of model inputs can be found in Appendix B.

- Operator Income[35]

Operator training is considered a one-time expense at the outset. Node hardware costs are one-time capital expenditures made whenever a node is installed. Maintenance is a recurring cost equivalent to a percentage of total network node cost (which grows with the size of the network). Uplink bandwidth scales with the number of users, according to the formula described in the Network Dimensioning section (3.2.2). Lease fees for tower space are a static recurring cost that remains the same over the life of the network. For the most part, licensing fees recur annually and scale with the number of nodes[36]. Interest expenses scale with the total debt incurred by the operator. When applied[37], enforced operator income is a fixed value over the life of the network[38].

The only revenue stream is assumed to come from user subscriptions and installation fees. The number of subscribers is calculated at each step by multiplying the total coverage area of the network by the demand density at that time step[39]

For each set of inputs, the model explicitly identifies three critical points:

- ***C)*** ***Cash-flow positive***, defined as the point where the SSO's operational expenses, net of capitalized costs[40], are less than his revenue in a particular time step.
- ***G)*** ***Growth-sustainable***, defined as the point when the SSO generates sufficient cash flow to sustain the imposed growth rate without increasing his debt load
- ***P)*** ***Payback-period***, defined as the point where the SSO has repaid all of the debt (with interest) incurred while growing the network.

The model also calculates ***peak-debt***, defined as the greatest amount of debt incurred by the SSO during his or her expansion.

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[35] This expense will be dealt with separately, as it is not necessarily the case that the operator's income stream is derived directly from operating the network. Network operation could instead be a means to an indirect revenue stream such as movie rentals or IT services.

[36] In the model, the annual license fee for a node is paid at the time of its installation and annually thereafter.

[37] Because operating a CWN opens the SSO to a variety of indirect revenue generating opportunities such as IT services or home networking, we perform most analysis without the requirement of operator salary. This requirement will be applied at the end of the results section after we have identified the conditions required to make the network viable absent salary requirements.

[38] When a network grows beyond the point of repaying all debts, profits could be appropriated by the operator as additional salary. Because we are aiming to enable a business case where the operator pays back all debts in two years, it is reasonable to assume a fixed minimum salary (as opposed to correcting it for inflation or increasing operator ambitions).

[39] As discussed in section 4, we will investigate two demand cases, one where the demand is small enough that no mesh node ever has more than one subscriber and a second case where we begin with a plausible starting demand density and apply a demand growth rate that agrees with CCK statistics.

[40] Capitalized costs are costs for capital equipment, such as mesh node hardware.

Table 1 shows a sample model output for the first five steps of the base case described in the results. The three critical values are mined from the rightmost three columns. *C)* Occurs when the Cash flow column switches from negative to positive. *G)* Occurs when the accumulated debt for each individual timestep (Debt Subt. Column) switches from positive to negative. *P)* Occurs when the Total Debt column is less than or equal to 0. Peak-debt is the maximum value of the Total Debt column. This point should occur in the same period as (*G*).

Nodes	Users	BW	Node Cost	Training	Salary	Site Costs	Op. Lic.	Node Lic.	BW Cost	Maint.	Interest	Revenue	Cash Flow	Debt Subt.	Total Debt
	0	0	612	550	0	0	60		0	0	0	0	0	1223	1223
1	2.6	1273	425	0	100	250	0	120	155	0	9.32	119	-166	941	2163
2	5.3	1385	425	0	100	250	0	120	169	0.35	16.50	162	-144	919	3082
3	8.1	1499	425	0	100	250	0	120	183	0.71	23.51	206	-122	896	3979
4	11.0	1617	425	0	100	250	0	120	197	1.06	30.34	251	-98	873	4851
5	13.9	1738	425	0	100	250	0	120	212	1.42	36.99	297	-73	848	5699

TABLE 1: SAMPLE MODEL OUTPUT

As NPV is often considered a standard for financial analysis of infrastructure investments, it is worth noting why this model does not explicitly calculate a NPV value. Like the imposition of a fixed rate of growth, this is largely a design choice. In our analysis, we are not so much interested in the CWN for its degree of profitability against other investments as whether or not it would be a profitable, sustainable business on a short timescale. As a result, we include an income stream for the SSO as an operational cost and terminate the model when the SSO has paid back all debts. The model does not entirely neglect the opportunity cost of capital. Interest on accumulated debt is explicitly included in expenses at each period (fifth column from the right in Table 1) with the equation:

$$\boldsymbol{I = d * (((1 + r)^{\frac{1}{(12*g)}}) - 1)} \qquad \textbf{1.}$$

Where *I* is the interest in period *t* on debt (*d*) from period *t-1, g* is the growth rate in nodes per month and r is the APR. Such an approach is conservative because inflation, which we assume affects all costs and revenues equally, would likely increase real-dollar incomes over time, making past debts less expensive to pay off. As discussed in Assessing Outcomes (3.1.3), I believe that the four metrics (*C, G, P* and *peak-debt*) are more relevant to the motivation of the SSO than a traditional NPV value.

IMPLEMENTING POLICY CHANGES

The described model illustrates the effects of policy changes through the policies' impact on costs to the SSO (with respect to the model, this means changes in the input variables for prices and interest rates). Given our objective of enabling SSOs to spontaneously implement CWNs, policies' effects on the market conditions for the CWN are the most important consideration.

Nonetheless, there are some policy interventions that cannot be captured in terms of prices, and any given policy that affects a price can be approached in a variety of ways. With the model output providing our baseline requirements, we will address these final details in a more freeform discussion.

ASSESSING OUTCOMES

For each run, the model calculates the necessary scale (and implicitly the amount of time) required to reach each of the three critical points, as well as the size of peak-debt described in the Model Mechanics (3.1.2). The outcomes of each set of policy strategies can be directly compared by their ability move each critical point toward *t=0* and to decrease peak-debt from the base case. A (theoretical) "perfect" network would be sustainable for a node count of 1, with an investment of $0, while a completely failed network would be unable to grow sustainably before reaching the maximum size an individual SSO could manage[41].

If we assume that the SSO is an individual without significant available cash or a large existing income stream, the output metrics generated by the model are key considerations in the attractiveness of starting a CWN. From the perspective of the SSO, building broadband infrastructure is a highly speculative undertaking. Even if the SSO is confident in the existence of initial subscribers, he has little means to ensure their long-term subscription. Nor does he have any leverage against predatory market entry from large telecoms or abrupt, anti-competitive price changes from upstream suppliers (to name a few risks); and with the speed of market evolution in places like Kenya, it is difficult for anyone to predict what the broadband landscape may look like in 3-5 years.

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[41] We assume the maximum manageable size to be somewhere between 50 and 100 nodes, but the exact number would likely depend on density, terrain, available management tools and operator expertise. To think of it in concrete terms, a network where as many as 1 of 100 nodes fail each day would be undesirable, but manageable at the scale of 100 nodes (requiring the operator to make one on-site call per day). The smaller the scale of the sustainable network, the more resilient it will be in the event of conditions that cause widespread damage such as high winds or torrential rains, but we imagine that the simple equipment required to build the network can be installed to withstand all but the most severe conditions.

As a result of the above, two major discouraging factors for the SSO are the degree to which he or she must go into debt[42], and the duration of time he or she must maintain that debt. Because of the uncertainties and personal risks involved, a large up-front investment that becomes very profitable after 5 years is likely to be less attractive than a small investment that generates a reliable source of income in a few months.

The SSO's ability to accrue debt is also limited. As a personal investor, major banks such as Barclays enforce a maximum loan term of 72 months. This imposes a hard limit on the amount of time a network has to pay back capital investments.

One might also consider the amount of debt in terms of an individual's earning potential. To provide some perspective, Kenya's GDP per capita was $738 as of 2009 while an engineering student direct from university can expect a salary of at least $7,200[43]. It would be difficult to expect an individual to risk the equivalent of many years salary on a speculative venture, while an investment equivalent of as much as a year or two's salary might be more palatable.

A final consideration for the SSO might also be the minimum sustainable scale of the network (related to the time it takes to achieve sustainable growth by the imposed node installation rate). This could be relevant in the case where a village is particularly small or the sustainable scale is unmanageably large; however, we will find that scaling tends to be a less pressing variable than time unless the density of demand is very small.

An example set of criteria for viability might then be:

- ***Peak-debt incurred debt is less than two years of the operator's salary***[44]
- ***Growth-sustainability is achieved within the first year***
- ***Payback-period is less than two years***

The exact values for these criteria would further depend on the terms of incurred debt and a more nuanced knowledge of local market risks, but we will use the above as a starting point.

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[42] In my own [anecdotal] experience, Kenyans are debt averse and often prefer to take "pay as you go" options at high premiums than to take on loans or other obligations that have a lower total cost. An excellent example of how this manifests is in the way Kenyans purchase mobile internet access. While the /MB rate for large data bundles is much lower ($0.005) for large data bundles than small ones (up to $0.04), many individuals prefer to buy bundles in much smaller sizes than they can afford.

[43] Based on assertions by University of Nairobi Engineering Dept. Faculty

[44] Salary is assumed to be $200/mo., thus the target here is $4,800.

ASSESSING POLICIES

Because there may be many ways to achieve a given outcome, a thought framework for comparing approaches is necessary. This is not meant to be an exact quantitative comparison (as there may be no analytical means or available data to make it), but instead a logical approach to thinking about the differences among approaches.

For this analysis, I am concerned with considering how proposed approaches compare with respect to two inexorable problems in providing incentives for infrastructure growth in telecom: The creation of perverse incentives (market distortions) and inefficient use of funds. One could imagine a comparison that maps these two variables to a parameter space as shown below:

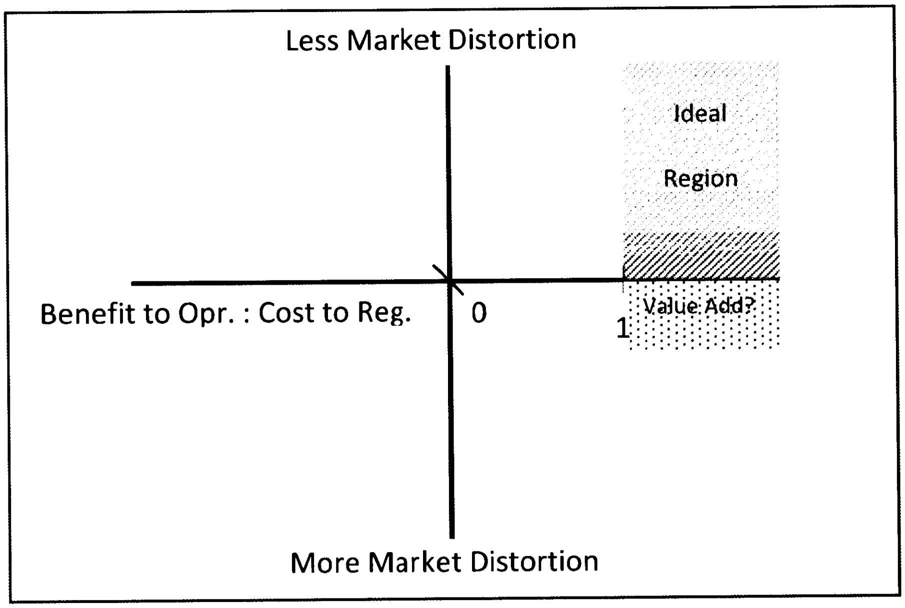

FIGURE 1: A MULTI-PARAMETER SPACE FOR EVALUATING POLICY INTERVENTIONS

In Figure 1 the X-Axis maps the benefit:cost ratio in terms of the amount that the investment gap is closed for the operator vs. the cost of closing that gap to the regulator. Policies with multiplicative returns would have a ratio greater than 1, while those with diluted returns would be less than 1. Policies detrimental to the SSO are negative, and we assume, for the purposes of the graph, that all policies have non-zero cost to the regulator from the base case.

For example, a demand side subsidy where individual consumers are provided vouchers for internet subscriptions would provide a benefit to the SSO equivalent to the value of the vouchers redeemed[45]. Running the voucher program would cost the regulator the value of the vouchers (redeemed by the SSO after users buy services) plus the cost of administering the voucher program. Thus, the benefit:cost ratio would < 1.

Alternately, the regulator could control the prices for wholesale bandwidth. Because there are only a few wholesale providers, managing such a program might be relatively inexpensive, however the benefits to all the SSOs could be very large and recurring, making a benefit:cost ratio >1.

The Y-Axis maps the degree to which a given policy is likely to distort the market away from the ideal of being technologically neutral and fully competitive. A neutral value here would leave the market unchanged, a positive value would improve the level of distortion (lessen it), while a negative value would distort the market further.

The issue of "what is market distortion?" is a highly subjective one. In my own opinion, a market distortion is any deviation of the market from our idealized view of what the perfect market should provide. In the perfect market, we would expect that the price of a service provided with any given technology to be directly related to the price:performance characteristics of the technology (in other words, no technology has an advantage or disadvantage exogenous to its performance); all serviced areas are covered by multiple independent providers with competing services; and new technologies are allowed free entry into the market. Further, we expect operators to serve all sites that are profitable based on the characteristics of available technologies and none of the ones that aren't. Under this definition, regulations that modify the market to correct market failures are anti-distortive.

In the above definition we can imagine that some policy imperatives, such as Universal Service, would require market distortions. In the case of Universal Service, these distortions come in the form incentives for operators to build infrastructure where it would otherwise not be profitable (This example would fall in area of the parameter space labeled *"Value Add?"* when implemented in a cost-effective manner).

On the flip side, imagine a situation where a company with a new (or alternative) access technology is priced out of the market by upstream providers protecting their vertically-integrated systems. In this case, market regulation mandating network interconnection might be anti-distortive because it prevents vertically integrated operators from pricing out a more cost-effective last-mile technology from a non-integrated provider (This example would likely fall into the *Ideal Region* of the parameter space).

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[45] This assumes that individuals are not paying more money out of pocket than they normally would have without the vouchers.

With the above in mind, a policy could be considered distortive if it does one of the following:

- Artificially (i.e. through non-market means) increases or decreases the cost of implementing one particular broadband technology vs. another, or limits the entry of new technologies into the market (A good example of this would be spectrum licensing fees);
- Treats any individual market player uniquely, other than to prevent the creation of monopoly conditions by the dominant operator; or
- Creates conditions that hasten market consolidation beyond the point of effective competition or encourage anti-competitive behavior.

In the parameter space of Figure 1, policies in the top right are most desirable, and any policy in the shaded box could be expected to create net value.

This conceptual thinking is used as a basis for the concluding policy discussion

MODEL PARAMETERS

The model design, as explained above, finds its conceptual and underlying physical root in a CWN pilot conducted in two locations outside Nairobi (one peri-urban, one rural) beginning in the fall of 2010. The physical system explained below is largely analogous to that which we used in the Kenyan pilot, as well we use experiences and network data from the Kenyan pilot to inform bandwidth usage and patterns of growth, respectively.

The Keynan project was not the first network built on the Fabfi platform, but instead an evolution of an earlier system, constructed in Jalalabad, Afghanistan in 2009, that still operates today.

The following sections (3.2.1-3.2.10) discuss each of the input parameters to the cost model described in 3.1.1 and 3.1.2, the parameters' underlying assumptions and potential limitations.

MESH INFRASTRUCTURE

A mentioned in the introduction, this analysis has chosen to focus exclusively on the extension of mesh networks beyond the fringe of existing NGN coverage by building wireless links from existing fiber-connected radio towers. While this is both a useful application, and a well-controlled case to analyze[46], it is worth noting that similar networks extending much farther from existing coverage than considered here can—and have—been built with all-WiFi infrastructure (R. K. Patra 2009, pp.16–18). Many of the principles discussed herein would also apply to such networks.

ARCHITECTURE

The basic design of the network, depicted in Figure 2, is an infrastructure mesh using multiple radios and multiple channels per node.

Unlike a simple, ad hoc mesh, which has scaling limitations as described in Gupta & Kumar (2000), an infrastructure mesh operating on multiple channels can achieve 100% end-to-end throughput with respect to the capacity of its individual PtP radio links when configured correctly (Brzezinski et al. 2008). It is the removal of the scaling limitation, combined with the performance gains realized under 802.11n, that make wireless mesh a viable alternative to carrier-class technologies in many applications.

The mesh network described neatly follows what might be considered best-practice for a high-performance wireless network, using a backhaul layer and an access layer operating on separate frequency bands. It is to be noted that this architecture is one of many variations on a general theme. In the case of the Kenya network, we optimized for homogeneity in hardware, highest performance and lowest likelihood of needing to reconfigure any given node in response to growth. Alternatively, one might adopt a hybrid architecture where access nodes perform double duty as ad hoc backhaul to decrease the number of dedicated backhaul links and decrease overall cost[47], or a number of other designs. For the purpose of analyzing the CWN business case, the first design is preferred for its simplicity (on average, all nodes are the same), guaranteed performance and similarity to the Kenyan field trial.

This mesh is divided into three logical components:

a. Long-distance backhaul between the nearest commercial service and the target site;
b. A local distribution network at the target site to serve access points; and
c. Access points within the distribution network to provide wireless service to clients.

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[46] Mainly because we avoid the need to consider the cost of building towers

[47] It can be shown that this approach can also be managed to a performance boundary that is constant with scale, provided the ratio of uplinks to ad hoc nodes remains constant and uplinks are well distributed (Agarwal & Kumar 2004).

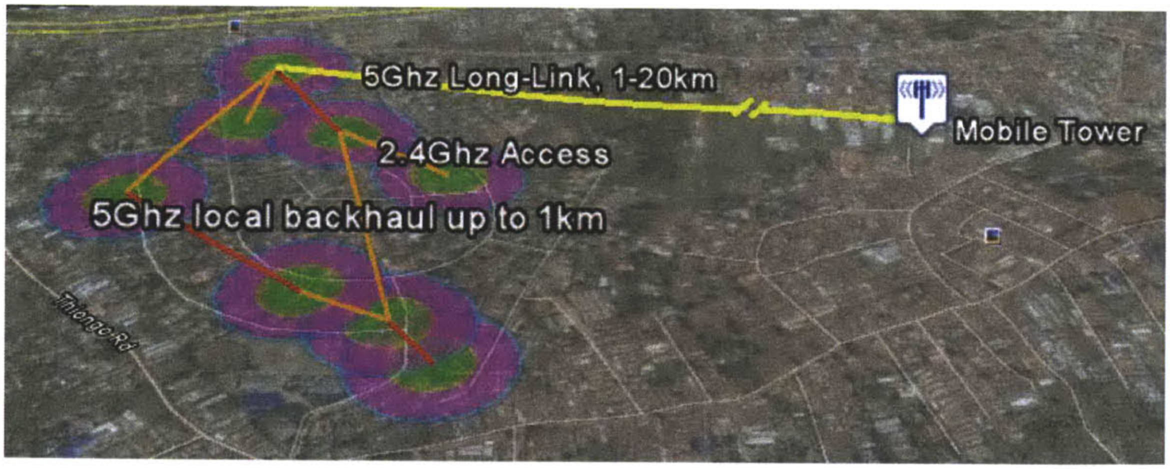

FIGURE 2: SCHEMATIC DIAGRAM OF A DUAL-BAND WIFI MESH WITH LONG-DISTANCE BACKHAUL[48]

The ***long-distance backhaul (a)*** consists of a single directional wireless link between the local site and a remote radio tower. Off-the-shelf hardware as specified in our cost model is capable of links exceeding 20km with goodput[49] of 60Mbps or more[50]. Links of this length can be made between a 75m tower and a rooftop using a radio on a small pole. For a network where most traffic flows to and from the public internet, the backhaul is the primary limiter of network capacity.

The ***distribution network (b)*** is constructed from individual network ***nodes***, each of which is made up of one or more individual wireless networking ***devices*** that provide connections either to ***clients*** or other nodes in the distribution network. The distribution network operates on the 5Ghz[51] frequency band. Nodes carrying transit traffic from other nodes back toward the gateway are configured with paired radios to prevent throughput degradation. In a typical implementation we also expect the distribution network to implement redundant paths to the gateway, whether via meshing or statically configured cross-linking. This redundancy comes at a small equipment cost which we account for with the assumption that every mesh node always

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[48] Image capture from Google Earth http://earth.google.com with custom icons from http://mapicons.nicolasmollet.com

[49] Goodput is a networking term referring to the application-level data throughput over a communication link. This differes significantly from the hardware bit rate of a connection. For example, a 802.11g wireless link has a hardware bitrate of 54Mbps, but its theoretical maximum application-level data throughput of about 27Mbps (Gast 2003)

[50] Best-case theoretical goodpuput for the backhaul devices used in our Mt. View network approaches 100Mbps, but I have never observed these values outside of the test lab.

[51] 802.11n devices typically operate on either the 2.4 or 5Ghz frequency band. Client devices are almost always 2.4Ghz capable, while only some implement both bands. As a result, the 5Ghz spectrum is typically less crowded and is more commonly used as the backhaul band in multi-band WiFi networks. In most places, including Kenya, power restrictions are also less restrictive in the 5Ghz band, which is advantageous for long-range transmission.

has three radios. The devices used in our specification can trivially make links up to 1km at 60Mbps with clear line-of-sight. Much longer links are also possible with inexpensive RF reflectors.

The ***access network (c)*** consists of 2.4Ghz wireless devices attached to nodes in the distribution network. Their primary purpose is to connect clients. The performance of access devices is the primary driver of the cost of coverage (based on the amount of area a single device can cover) and provides an upper bound on the number of simultaneous client connections can be supported (based on their throughput capacity). In the ideal case, access nodes have similar throughput as distribution nodes; however, communication with less capable hardware or clients with poor signal strengths can have a significant effect on performance[52].

For a more detailed discussion of the calculations and considerations behind the above claims, refer to Appendix H.

HARDWARE

While earlier developing-world wireless mesh projects have had difficulty using off-the-shelf hardware in harsh environments (Surana et al. 2008), commercial companies[53] have now begun to integrate many previously-unavailable, but useful features such as TDMA radio protocols[54], POE support and robust power supplies. In our network, all the components, excepting a few power connectors, are available off the shelf. Off the shelf components significantly decrease the expertise required to build the networks in the base case because new operators can buy purpose-built equipment at low cost instead of cobbling systems together from components that were not intended for WISP use. It is worth noting that some of the system, particularly the power supply, could be built from discrete components for a slightly lower cost, but this analysis assumes store-bought components.

THE MESH NODE

The mesh node, as shown in Figure 3, consists of a single access radio, one or more radios for the distribution network and an uninterruptible power supply that is capable of charging from AC power and is able to provide up to 24hrs of backup power. These components are integrated into an enclosure with a mounting bracket and attached to a

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[52] To be discussed in detail in Network Dimensioning, section 3.2.2

[53] See Ubiquiti Networks www.ubnt.com and Mikrotik wireless www.mikrotik.com for examples.

[54] TDMA is an alternate channel access sharing protocol (standard 802.11 is CSMA/CA) that allows greater performance in extremely long (>20km) links or heavily shared channels. None of the networks discussed here would require TDMA to perform adequately.

5m pole. Node cost varies according to the number of radios used, as well as the need to incorporate solar power. The total cost for a mesh node in each of the possible configurations is provided in Table 2. It is assumed that each node uses one radio for client access and the others are used for backhaul connections. See Appendix A for details.

Node Type	Cost
Double Radio Mesh Node	$309
Triple Radio Mesh Node	$425
Quad Radio Mesh Node	$517
+ Solar	$250

TABLE 2: PRICES FOR MESH NODES AND COMPONENTS

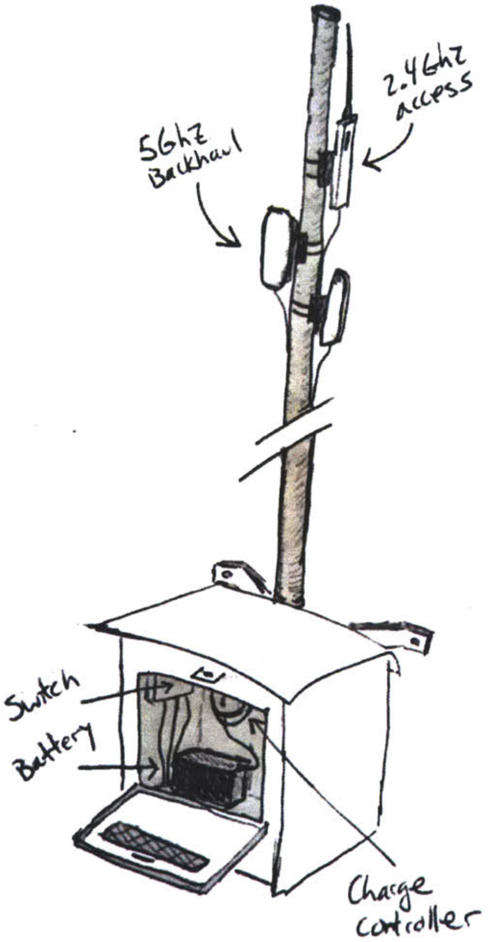

FIGURE 3: THE MESH NODE

Past researchers have found that cleaning grid power is a major concern for systems operating in developing countries. In our Kenyan experience we have found that the quality of power decreases as a function of distance from Nairobi. Neither our test lab in the city nor our first pilot on the urban fringe experienced any power abnormalities sufficient to damage equipment. Inexpensive UPS systems were sufficient to prevent router hangs as well. By contrast, our second pilot site roughly 60km north of the city experienced power supply failures similar to those described in Surana et al. (2008). Despite our focus on areas immediately surrounding cities, we have included power supplies having wide voltage input ranges and a basic level of surge protection to ensure that we do not underestimate costs.

The cost of solar power is shown in Table 2 to illustrate the expense associated with operating off gird; however, for peri-urban Nairobi, the assumption of at least intermittent grid power is appropriate and solar panels will not be included in the model's node costs.

LONG-LINKS

By taking advantage of existing commercial wireless towers, it is possible to make links of 20km or more with very little hardware. In this study we assume that this link can be accomplished using a pair of radios with integrated antennas costing between $175 and $240 a pair (Kenya price), depending on the length of the link. With the uplink radio affixed to a commercial radio tower, the remote end of the link is easily affixed to the mounting pole of an existing mesh node. The costs in Table 3 also allow for power backup at the head end and additional battery capacity at the remote end. Prices are as follows:

Link Distance	Cost
up to 10km	$295
>10km	$354

TABLE 3: PRICES FOR LONG-LINK BACKHAUL EQUIPMENT

Wireless links optimized for long-range transmission have been shown to provide broadband-quality throughput at distances of hundreds of kilometers (CISAR 2007).

NETWORK DIMENSIONING

The first component of the system model describes how bandwidth the needs grow as more users are added to the system. In residential broadband applications, the maximum data rate provisioned to each customer, multiplied by the number of customers, is typically much greater than the total capacity of the network. Because traffic flows in an IP network are generally elastic and use is intermittent, network operators can use stochastic models to determine total network capacity such that users generally experience a specified transfer speed greater than their fractional share of the total network capacity. When considering all traffic alike, such models have the useful feature that an individual user's expected performance on an aggregated line of a given capacity can be calculated as a function of the individual users' physical link capacity and user demand (J. W. Roberts 2004). Bonald et al (2003) go on to show that the analytical solution to such models can be approximated very accurately[55] for even relatively small numbers of users (N=50) using the formula in Equation 2.

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[55] Some limitations to this formula are worth addressing. First, it assumes completely elastic traffic, meaning that an individual user's flow can increase in speed to utilize all available bandwidth or decrease in speed in response to congestion. For most traffic on the web such assumptions apply to a certain extent. Assuming the capacity of the local network is the bottleneck, simple web browsing, emailing, and file transfers are all completely elastic flows. *(Continued on next page...)*

$$C = \frac{N}{\frac{1}{a}+\frac{1}{d}-\frac{1}{c}} \tag*{2.}$$

Where C is the total aggregated capacity of all users, a is the average offered load[56], d is the minimum useful speed and c is the individual user's link speed (Bonald et al. 2003).

Investigating the implications of Equation 2 under a fixed load and fixed useful rate reveals two interesting features. First, for groups of more than a few users, the amount of bandwidth required *per user* *(C/N)* depends only on the characteristics of the individual user connections, not the total number of users. Second, the amount of system bandwidth (*C*) required *decreases* as the peak speed of individual user connections increases. The first of these two results is seen by dividing both sides of Equation 2 by *N*. For the second we can employ a simple example:

Imagine that a group of 50 users were provided connections with a link speed (*c*) of 2048kbps and an offered load (*a*) of 100kbps. If we want these users to experience a useful speed (*d*) of 1024kbps, Equation 2 would yield a required system capacity (*C*) of 4767kbps.

Now, imagine that these 50 users were allowed an individual link speed (*c*) of 4096kbps instead of 2048kbps. Using Equation 2, the total bandwidth required is now 4659kbps.

Buffered streaming video and audio are as well, within limits; however the elasticity assumption does not apply to real-time traffic such as VoIP and audio/video teleconferencing. In the case of real-time traffic, fixed stream rates, latency and jitter requirements prevent buffering and speeds cannot be decreased without damaging the fidelity of the message.

An additional complication worth noting is that fair sharing does not necessarily have the same utility for all types of traffic. For example, decreasing the load time of a web page that normally takes half a second to load by a factor of 5 may not be particularly disruptive, while streaming a video on a connection at slower than the required bit rate likely ruins the viewing experience for the user. The implementation of QoS routines can be used to increase the perceived performance of the network for any given bandwidth; however, I leave the inclusion of this detail and the inevitable, heated discussion of net-neutrality for further work.

Regarding the management of inelastic streams; for the purpose of modeling capacity requirements we can ignore inelastic streams as long as their throughput requirements are less than the user's actual, un-contended share of the total capacity. Based on our assumptions for BHOL, the network could reasonably be configured to guarantee users basic video chat regardless of load.

[56] Typically average load is calculated during a user's busiest online hour and called BHOL or Busy Hour Offered Load (Federal Communications Commission 2010, p.111) See Appendix C for details on calculating BHOL.

Thus, increasing the individual user's peak speed has the effect of increasing the number of users that can share the same uplink capacity at a particular useful rate.

The feature of decreasing bandwidth with increasing link speed can also be seen by simply taking the derivative of Equation 2 with respect to *c*, holding *a, d* and *N* constant, which yields (by the quotient rule):

$$\frac{dC}{dc} = \frac{-N}{c^2\left(\frac{1}{a}+\frac{1}{d}-\frac{1}{c}\right)^2} \qquad 3.$$

Parameter *c* must be greater than both *a* and *d* because the link speed must logically be greater than both the offered load and the desired useful rate. Therefore, the portion in parentheses in Equation 3 will always be positive and the derivative of the system capacity (*C*) with respect to increasing *c* will always be negative.

Unlike a large ISP using DSL, mobile or fixed-cellular, where the capacity of the individual user link (*c*) is often the performance bottleneck, local link speeds to individual users in the CWN continue to exceed the speed of the uplink capacity (*C*) until the system scales into the hundreds of users. Until this crossover point, the maximum speed an individual user can achieve increases with each additional user.

Reorganizing the Equation 2, we can solve for the capacity required to serve a group of users if each user is allowed 100% of the network's capacity as his or her peak rate. To make this change, we substitute *C* for *c* and solve the equation for C[57], as shown in Equation 4.

$$C = \frac{(N+1)ad}{a+d} \qquad 4.$$

Equation 4 is satisfied as long as required $C > d$[58], but will need to be modified for small values of *N.*

The contention ratio (*r*), defined as the number of times the operator over-subscribes his uplink capacity with respect to the useful rate he expects the user to receive, is then calculated as shown in Equation 5[59]:

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[57] Note, that $ad/(a+d)$ is the same as $1/({}^{1}/_{a} + {}^{1}/_{d})$

[58] *C* must be greater than *d* because it's not possible to provide a useful speed larger than the total capacity of the system. For very small values of *N* the total capacity (*C*) given by the approximation is smaller than the useful rate, which is an illogical result. This is why we modify the approximation for small values of *N*.

$$r = \frac{dN}{C} \qquad 5.$$

Figure 4 graphs the total required uplink bandwidth and contention ratio with respect to the number of users given a BHOL of 100kbps[60] and a useful rate of 1024 kbps. Notably, the graph shows that at the scale of 100 users, the wireless links are operating nowhere near their theoretical capacity.

Because the CWN is initially providing services to a small number of customers and purchasing a relatively small uplink, it uses capacity less efficiently than a provider serving hundreds or thousands of customers; however, the ability of the CWN to deliver very high LAN speeds (*C=c* up to hundreds of *N*) gives CWNs an advantage over cellular providers, whose individual link speeds (*c*) are limited by channel bandwidth, once the CWN scales to an uplink (*C*) that is larger than the (*c*) of the competing technologies. Labeled vertical lines on the graph in Figure 4, on the following page, compare peak transfer speeds for EV-DO (faster) and WiMax (slower)[61].

Based on an offered load of 100kbps and useful rates of 1024kbps, a single uplink system could support a maximum user base of roughly 600 users.

In modeling the CWN, we also need to calculate bandwidth requirements for small numbers of users where the approximation from Equation 4 is less accurate. For this region (1-20 users), the model adds the useful rate to the output of the approximation (for *d*=1024kbps and one user, this gives a requirement of 1206kbps). The additional 1024kbps is then decreased linearly over the first 20 users until the above approximation is un-augmented. This modification compensates for the tendency of Equation 4 to underestimate bandwidth requirements for small for small numbers of users.

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[59] Note: this is a slightly non-standard use of Contention Ratio. Generally the contention ratio would be the ratio of the "offered" rate (usually the peak rate) and the *(Continued on next page...)*
total Capacity per user or: *Nc/C*. We are using a nonstandard rate here because we're using the unusual approach that every user can use the entire available capacity if available.

[60] See Appendix C for details on BHOL.

[61] The speed provided for EV-DO is Rev B, which has an average peak download rate of 3.75Mbps. Peak performance falls off toward the cell edge to 1.5Mbps (Qualcomm, Inc. 2007). WiMax speed is the highest business (likely un-contended) speed offered by any provider, but is much less than the capacity of the technology.

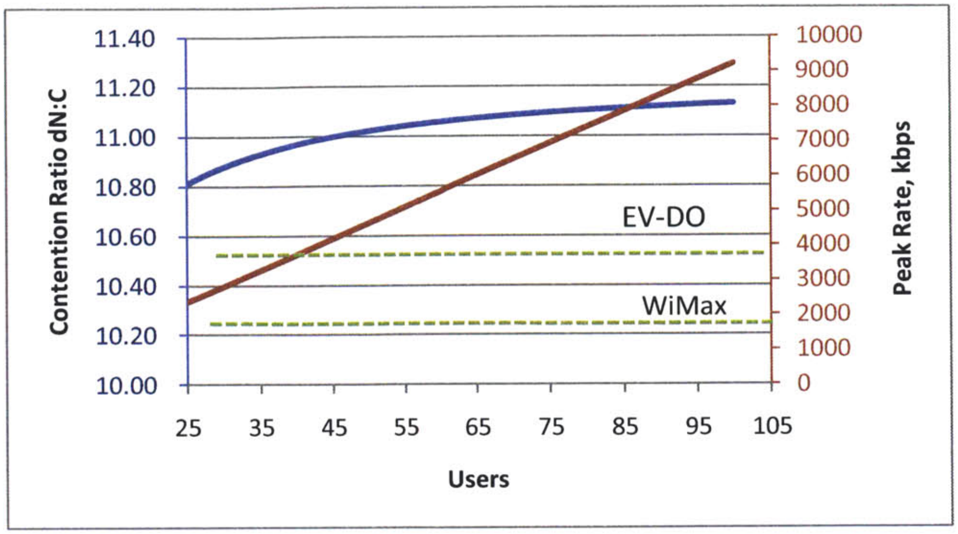

FIGURE 4: 2 CONTENTION RATIO VS. NO. OF USERS; USERS OFFERED FULL UPLINK SPEED[62]

BANDWIDTH COSTS

Much like the price of goods in a Kenyan village market, the price of bandwidth depends as much on who you are as the underlying cost of what you're buying. Commercial providers are very guarded about their costs, and retail bandwidth prices can range from over \$400/Mbps to as little as \$250/Mbps. These prices make reselling retail-priced, dedicated connections difficult; however there is some evidence to suggest that the actual costs of delivering dedicated bandwidth to Nairobi are much lower.

Our best estimate of the actual cost of internet connectivity comes from KENET. As the bandwidth provider for all of Kenya's major educational institutions, KENET maintains a broadband supply chain from an internet exchange in London all the way to end-users in every region of Kenya. KENET generally tries to lease, as opposed to own, infrastructure whenever possible, but is otherwise very similar to other Kenyan ISPs; and as a non-profit organization, they were happy to share their costs.

The majority of KENET's cost still comes from providing international capacity. Capacity over submarine cables to London costs KENET \$80/Mbps for leased lines. Adding in terrestrial leased lines and IP transit on the remote end brings this cost to \$123/Mbps.

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[62] It is worth nothing that because the approximation to required bandwidth underestimates bandwidth requirements for small *N* and large *d/c*, the savings attributed to scale are likely to be larger than what is depicted in the graph.

Domestic leased line capacity and operational overhead[63] brings the total cost to about $150/Mbps.

While only a few years ago the cost of bandwidth was synonymous with the cost of international bandwidth, peering arrangements through KIXP[64] now allow domestic traffic to remain domestic. KIXP members pay $240/mo for up to 1Gbps of peering capacity and the benefit of avoiding international transit costs for local bits. Increasing web presences from domestic sources and the recent introduction of Google web cache (Hernsman 2011) are steadily increasing the amount of user traffic that remains in Kenya, which tends to lower the cost of providing internet connectivity; however, without operator data it is difficult to know by exactly what fraction.

For the purposes of this analysis, we will explore both a conservative and a slightly more aggressive "competitive" price: $150/Mbps which we know is break-even in the case of 100% international traffic, and $100/Mbps which assumes greater cost reduction from domestic peering. $250/Mbps is used as the retail price.

COVERAGE AND GROWTH

In the traditional conception of last-mile growth, a particular area is targeted for deployment and coverage is rolled out monotonically from the POP into the target area. In the case of fixed line networks, there is some flexibility toward phased rollout; however, initial capital investments for active network components tend to dominate at smaller scales, and high take rates along deployed lines are essential for success (DSTI/ICCP 2008). Commercial wireless technologies, such as mobile-cellular and WiMax, are much less sensitive to the distribution and density of users but, according to a local WiMax Provider, require minimum investments on the order of $40,000, even assuming shared towers[65].

In each of the three pilot projects I have been a part of over the last three years, we observed that the natural growth of networks progressed according to a considerably different model. Instead of expanding blanket coverage steadily outward from the site of the uplink, operators identified early adopters as sites for initial nodes, connecting these nodes together with links ranging from a few hundred meters to several kilometers. Once small islands of connectivity were established, users in proximity to the initial adopters tended disproportionately to take advantage of the service availability, becoming subscribers themselves. At the same time, word of mouth from

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[63] KENET adds 10% for overhead.

[64] Kenya Internet Exchange Point http://www.kixp.or.ke

[65] $40k costs quoted in an interview with Riyaz Bachani, CTO of Wananchi Group, Kenya.

existing subscribers generated new leads for early adopters to host additional nodes. Qualitatively, the net effect of such behavior was a subscriber base with higher density clustered around the locations of early adopters. If we view the adoption of broadband services as a diffusion of innovation[66], this result is not surprising; however, it is a striking contrast to the way current commercial systems grow[67].

While it is likely the above growth model will result in a better business case for the CWN, we lack the data to determine exactly what degree of clustering occurs. The model makes the conservative assumption that no clustering occurs. We model the number of subscribers at each time step by assuming an average footprint for a household, then dividing the total coverage area of the network by the household footprint, then multiplying by the demand fraction:

$$\boldsymbol{Subscribers} = \frac{(\boldsymbol{Network\ coverage\ area})}{(\boldsymbol{Household\ Footprint})} * (\boldsymbol{Fractional\ Household\ Demand}) \qquad \textbf{6.}$$

Because the overall number of internet users in Kenya is growing very rapidly, the model also adds a term for constant demand growth[68], which increases the total demand fraction at each step by the equation:

$$\boldsymbol{D_t = D_0(1 + \frac{tr}{24})} \qquad \textbf{7.}$$

Where D_t is the demand in period t, D_0 is the initial demand, r is the annual growth rate with respect to the initial demand and 24 is the number of periods in a year (based on a node installation rate of 2 nodes/mo.).

Table 4 lists the cost to build a wireless system for a specified number of users using the continuous expansion strategy assumed for the CWN. Results are shown at four different penetration levels[69], including the minimum user density (1 user/node). For comparison, the capital cost to serve users with WiMax base station with a microwave

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[66] As described in Greg Orr's review (2003) of Rogers' *Diffusion of Innovations* (1995)

[67] Because the mesh network adds users within areas of existing coverage with no additional capital cost, a network that grows virally—and as such achieves local areas of greater subscriber density—has the attractive feature of decreased deployment cost per subscriber.

[68] The model adds the same number of users each year, as opposed to compounding growth. This approach provides more conservative outcomes than the exponential alternative. Conservatism is preferred because we do not know if the user growth in Kenya will reach an inflection point in its user growth curve in the near future.

[69] Note that the because of the high user growth rate in Kenya (We use a growth rate of 35%. The last annual growth rated quoted by CCK was 71.8% (CCK 2011d), assuming 2 internet users per household, we divide this rate in half) penetration at the beginning of a network deployment would be lower than the penetration at the time when the network grows to 200 users. Thus, user growth occurs from both the addition of nodes and an increase in the number of subscribers at existing nodes. The penetration rates shown in Table 4 are the penetration rates at the time the network reaches 200 subscribers.

backhaul is also shown. Price for a base station is as quoted by a Kenyan WiMax operator[70].

Total Penetration at 200 Users	Users/Node	CAPEX to serve 200 users	Time to reach 200 Users
1 user/node (7.7%)	1.0	$85,000	100mo.
10% Penetration	1.3	$65,000	77mo.
20% Penetration	2.6	$32,700	39mo.
30% Penetreation	3.9	$21,700	26mo.
WiMax (200 users / base station)	N/A	$49,500	N/A

TABLE 4: CAPEX AND TIME TO REACH 200 USERS BY FINAL PENETRATION RATE

Looking at

Table 4 , we take three messages to heart. From the perspective of capital costs (CAPEX), the mesh system has a competitive advantage in two scenarios: First, mesh is preferable when penetration is large enough that there are multiple subscribers per mesh node. An additional advantage of the mesh, in this regard, is that a mesh network need only deploy coverage in areas where there is demand, allowing small groups of users to be served with less cost. For example, in geography where small clusters of residents are dispersed an a largely unpopulated area (imagine a town with a lot of surrounding agricultural land), the mesh can achieve higher subscriber densities per unit area covered than more centralized PtMP approaches such as WiMax. Another situation where the mesh has an advantage is when subscriber density is low enough or terrain is difficult enough that a centralized base station cannot saturate its capacity. Even in an area with low average demand, a mesh can reach schools, hospitals or small businesses that desire high-performance connectivity for the cost of only a few mesh nodes. In the general case, the maximum capital cost to connect a new user will never be much more than the cost of a single mesh node. The third message from the above chart is that, as demand decreases, the CWN takes longer to expand to the same number of users[71].

SITE COSTS

For traditional broadband providers, the need to "feed and house" capital equipment represents a significant cost. For example, tower costs account for roughly a third of lifetime cost of a cellular base station (Federal Communications Commission 2010, p.81). Even when only wires are involved, the costs for rights of way can be prohibitive.

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[70] Note, this comparison is conservative, as a $40,000 cost assumes an existing tower at the target site.

[71] This could be mitigated by the existence of multiple CWNs or CWNs with the ability to install nodes more quickly.

According to Kenya's permanent secretary for ICT, commercial providers have recently blamed excessive site fees charged by local councils for driving up last mile costs (BiztechAfrica 2011).

In our experience, the CWN model virtually eliminates site costs in the local service area. Across three years and three network pilots, we have never needed to pay for electricity or roof space. Because individual network nodes are small and self-contained, site prep is minimal, rarely consisting of more than bolting the node to the roof and finding a convenient electrical outlet. The simplicity of installations also decreases the need for periodic maintenance, which essentially amounts to little more than replacement of backup batteries as they wear out[72]

In our two Kenyan pilots, early adopters were willing to both host nodes and pay for the services they provided. These extra costs, while small, are not trivial. Electrical service for a typical node costs roughly $25/yr[73]. By shouldering siting costs, early adopters gained access to the best wireless signal and highest speeds, as well as the ability to ensure the node remained powered. This tradeoff seemed to be attractive for subscribers in general.

The willingness of subscribers to absorb site costs has a dual benefit for the operator. Clearly the reduction of operating costs is one of these. The other benefit is that building a relationship with the early adopter—likely one of the more affluent, more tech savvy (or both) members of the community—provides the operator a tacit technical support technician and neighborhood advocate for the technology. The combination of reduced site costs and user participation in basic support activities likely reinforce the reliability and perceived value of the network to potential customers, as well as decreasing the need for the operator to make site visits to address trivial problems.

One cost that may be impossible to avoid is the cost of renting tower space. According to the local WiMax provider who provided tower space for our pilot, their lease for a single tier of space on the mobile tower with associated rack space costs about $500/mo. Given the small size of our transmitters, this space could easily house as many transmitters as there is available spectrum (about 10), making a minimum cost of $50/mo. for a shared tower.

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[72] The lifetime of backup batteries varies broadly based on their use. Surana et al. report 2yr rated batteries lasting as little as 3mo, which they attribute to poor charging (2008). With LVD circuits built into power systems and the Nairobi area's relatively clean (if unreliable) power, we would not expect a significantly shortened battery lifetime.

[73] Based on a node power draw of 12W and KPLC residential tariffs (KPLC 2008)

LEGAL / REGULATORY[74]

In Kenya, fees for even shared-access spectrum can be prohibitively expensive. For example, a single 20Mhz channel in the licensed microwave range would incur an annual fee exceeding $9,000. A CWN might use as many as ten times this amount of spectrum in a single network. Fees for exclusive spectrum licensing and use such as those for mobile cellular or WiMax are even higher (CCK 2011b).

As a result of high frequency fees, operation in an unlicensed frequency band is a distinct advantage for the CWN in Kenya. Such freedom, however, may be tenuous: In the strictest interpretation of CCK regulations, CWNs would be required to register all of their AP locations and pay a frequency fee of roughly $120 per AP per year (CCK 2011c).

Despite the above, in my numerous discussions with leaders inside Kenya's regulatory authority and ICT board about our pilot, the requirement of license fees or registration for our operation was never once mentioned. On the contrary, the idea that local operators could simply set up networks without fanfare was something that excited most of those with whom I spoke.

The CWN appears to take advantage of an exception to the licensing rules, namely:

> *This, however, does not apply to a WAS system, with coverage and/or range that is restricted within a building and/or campus (CCK 2011c)*

But it would take a rather liberal reading of the regulations to interpret the CWN as being restricted to within a building or campus. It is perhaps the case that CWNs "draw a bye" on CCK scrutiny because of their small scale. There is a healthy respect for small scale entrepreneurship in Kenya. As of 1999, the country had more than 1.2 million micro and small enterprises (McCormick et al. 2003, p.13), and operations smaller than a certain size generally avoid government scrutiny. For many communities, the CWN would certainly fall within that size.

It is possible, as well, that these regulations are simply not enforced. To give a related example, Kenya power requirements for devices in the 2.4Ghz band are unusually restrictive and would be violated by much of the equipment used for WISPs here in the US[75]. Nonetheless it is easy to find legitimate licensed retailers in Nairobi selling

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[74] Note: this section focuses on licenses and fees specific to network and radio transmission operators. Basic business licensing, by comparison, is an insignificant cost.

[75] E.I.R.P. limits in the US are 4W across for both 2.4Ghz and 5Ghz devices. It is worth noting that because coverage is typically limited by client devices such as laptops *(continued on next page...)*

equipment that violate these rules. In any case, the ambiguity around this issue certainly warrants addressing.

If CWNs were ultimately required to pay license fees for APs, the total fee required for a saturated AP would amount to somewhere between a quarter and a half of the usage fees required for a WiMax or mobile system[76]. The major difference, of course, is that, in the ideally demand-driven CWN model, a saturated AP is by no means the norm.

From an organizational perspective, the SSO is too small to show up on the regulatory radar screen as any of the classes of licensed entities[77], yet operating under the radar precludes the CWM from accessing the benefits of fair competition and interconnection regulations. The licensing required to access these benefits would be prohibitively expensive at the scale of a single operator.

In this analysis, we include per-node license fees in the base case. The results with license fees included pushes license fee elimination to the top of the list of policy imperatives.

HUMAN CAPITAL AND EXPERT SUPPORT

Until now, we have focused primarily on the technological characteristics of the CWN; however this is only half of the equation. For a large-scale commercial operator, expertise can be taken for granted; the advantage of scale allows operators to in-source technical professionals for key disciplines, spreading their cost out among a large subscriber base. The CWN conspicuously lacks this advantage.

In the conception of a CWN where local entrepreneurs build networks in their own communities, the expectation that the average operator possesses all of the technical and management skills to deploy, manage and monetize a WISP is difficult to fulfill. The subject of building and operating a WISP is a complex one. To give some perspective, the largely regarded DIY cookbook for rural WISPs, *Wireless Networking in the Developing World*, is over 400 dense, technical pages, while only touching on the bare bones of most topics (Flickenger 2007).

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and smartphones that operate at lower power levels with lower gain, even Kenyas's relatively restrictive power requirements are not incompatible with the WISP concept, provided long-hall links are accomplished in the 5Ghz band.

[76] This does (conservatively) not include fees for exclusive assignment of bandwidth, which would increase the cost for WiMax and mobile systems.

[77] Most ISPs are regulated as "Network Facilities Providers". Such providers incur the higher of $2500/year or 0.5% of revenue as a license fee. At its natural scale, the CWN operates more like an extended public communications access center, which would incur no fee, but does not provided the same benefits in-terms of interconnection requirements and protection from anti-competitive behavior.

For those without significant technical expertise, even a basic level of understanding can take hundreds of hours to achieve. On the flip side, those with formal training and experience (especially those with university degrees) are valuable commodities in the workforce and difficult to retain as operators unless the CWN can provide a stable, competitive income or be operated in tandem with professional employment (Flickenger 2007, p.323).

In our experience with university students in Kenya, we also found that there is no substitute for hands-on experience. Our electrical engineering students required weeks in the field before developing the proper instincts for troubleshooting and improvising solutions to problems.

Even if free training were available or operators could self-teach[78], the opportunity cost of spending a month or more in intensive training is a significant barrier. An operator working alone would also need to invest in a minimum set of equipment to learn with, amounting to at least one or two nodes. This investment would need to be supported over a period during which he is learning and not generating income

To some degree, the human capital requirements to operate a network successfully can be mitigated by inexpensive, user-friendly technology that abstracts details from users. This could include, for example, device firmware with mesh-specific GUI configuration, visual feedback of signal strength for antenna pointing or built-in systems for remote management and monitoring. In essence, many pilot projects abstract details by pre-configuring systems for local installers. Unfortunately, as Surana et al (2008) explain, system failures that require in-depth knowledge of the underlying technology to diagnose and repair are inevitable. As a result, sustainable networks must either in-source the knowledge to address these failures or implement a means for engaging outside support.

In all, the knowledge barrier is probably the most difficult component to overcome in building CWNs and is an important differentiator from commercial alternatives. In terms of actual cost, one might consider the knowledge barrier equivalent to taking a low-level IT certification course. Comp TIA A+ is a 70 hr training course in computer support that is readily available in Nairobi for roughly $275 dollars[79]. Twice this cost ($550) will be used as a proxy for the knowledge cost.

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[78] Many resources are available for this, including WNDW(n.d.) , Wireless U(2010), and Meraka's Wireless Africa (2009), to name a few.

[79] http://computer-pride.com/course.asp?id=18&type=C

INTEREST RATES

Even for CWNs using commodity hardware, some capital investment is necessary; however, individual credit in Kenya is difficult to come by. Even as a small business, interest rates for bank loans are high. Barclays Kenya, for example, advertizes a minimum rate for a business loan as 14.9%, and no nascent CWN operator would meet the eligibility requirements (Barclays 2011). Individual loans from a traditional lender require pay slips from an employer, which we would expect many of our SSOs not to have.

Most SSOs would qualify for micro-credit, but such loans come at premium rates. Average micro-finance institutions in Kenya charge over 30% interest (MFTransparency 2010).

By contrast, the large telecom operators have little difficulty obtaining credit at low rates. Safaricom offered a $90M bond sale at 7.75% in the last year that was fully subscribed in just over a month (Ombok 2010)(Ombok 2011). This interest rate is scarcely at the rate of inflation, which has ranged between 2 and 24% over the last decade (IndexMundi 2011)[80].

For the purposes of our analysis, we assume that a SSO could secure a rate of 20%[81] on his own, and use 8% as a rate to illustrate what would occur if the CWN could achieve level financial footing with large operators.

SUBSCRIPTION FEES

The objective of the enabling the SSO is to bring the lower rates of NGN to those outside their reach. In determining prices, existing services provide natural limit cases.

In Kenya today, a user with access to only mobile data can purchase unlimited service at broadband speeds (where available) at a cost of $47/mo. using an Orange Telkom EV-DO modem. For roughly $35, a user can have unlimited connectivity through Safaricom, but with a throughput limitation of 128kbps. For the purposes of this analysis, we conservatively take the cost of a Safaricom connection as the upper limit of cost that would provide value to the consumer[82]. Customers with access to NGN service pay

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[80] We can only assume from the rapid take-up of the Safaricom bond issue that the expectations for inflation over the next few years in Kenya are on the low end of the historical spectrum.

[81] National Bank of Kenya offers an 18% loan rate with a 1% fee (http://www.nationalbank.co.ke/inner.asp?cat=tariffsinterestrates). I round to 20% in case of other hidden costs related to securing or paying the loan.

[82] A connection of the same cost but of higher performance would be considered of higher value to the consumer.

sharply lower prices. For example, Wananchi's Zuku service charges only $12/mo for a 1Mbps peak-rate fiber connection, with up to 8Mbps available for $48[83].

In our Mt. View pilot project, we received a positive response to subscription fees of $24 and $48, respectively for 512kbps and 1Mbps services. For the purposes of analysis, we will assume a price of $30/mo. for a service with an uncapped peak rate and a backhaul dimensioned to provide a useful rate of 1Mbps.

OPERATOR INCOME

As mentioned in section 3.2.7, the ability to generate significant income from the operation of a CWN is essential for the development and retention of competent operators; however, because the operation of a CWN presents a variety of opportunities for SSOs to generate income indirectly by offering additional services (IT support, procurement, training, etc.), it may not be necessary for the CWN to generate the operator's entire personal income. An attractive salary is also likely to differ by location. For example, a lower salary might be satisfactory in a more remote location where living costs are lower and a premium is placed on remaining near family and friends.

For the sake of this analysis, we will primarily examine the financial state of the network without operator salary included[84], adding a salary requirement to the sustainable system example in section 4.3.8 to observe its effect.

When discussing salary, we will impose the restriction that the CWN generate $200/mo. in income for the SSO. In the Nairobi area this is a small, but liveable, salary[85]. As perspective, this is about 1/3 of what a university-educated engineer would earn in an entry-level first job.

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[83] We do not know, however, what the contention ratios (and relatedly, the minimum useful rates) are for these connections, but as a point of comparison, a useful rate of 1Mbps would cost at least $4.50/mo. to deliver at KENET's costs.

[84] Upon reviewing the results it will be clear that simply making the system sustainable without operator salary is challenging, and excluding the operator salary initially allows us to more clearly see how the technological requirements relate to costs.

[85] My Kenyan collaborators paid about $120/mo. for rent in the city and were able to procure meals for less than $2/day, if necessary.

SUMMARY

To recap, the previous pages have progressively developed a method to answer the question:

"Can reasonable policy interventions be devised that will stimulate spontaneous demand-driven growth of small-scale wireless ISPs? "

We assume from the current absence of CWNs that the CWN does not present an attractive business case to SSOs without policy intervention. This may be because the sustainable initial scale is beyond their reach, because the regulatory environment is uncertain or because the individual SSO has a weak position in against existing operators.

In order to understand the case for the SSO, I create a simple simulation model to understand the financial gap a SSO incurs between startup and sustainability from revenue, based on a pre-defined rate of constant growth. The model considers the following major variables, for each of which we have developed estimations or functions:

- Total Bandwidth
- Bandwidth price
- Physical Capital
- Interest Rates
- Site Costs
- Licenses and fees
- Human Capital
- User Subscription fees
- Operator Income

Using the model with the above variables, we can run a simulation to determine the scale at which growth is sustainable and the investment required to reach that scale. We can then investigate the effects of different policies on this investment and scale. Specific values for items in the above list can be found in Appendix B.

Once we have seen how different policies affect the bottom line, we will develop and discuss a policy strategy that supports sustainable SSOs. Keeping the multi-parameter mapping in mind, proposed interventions will be discussed in terms of their cost to the regulator and their potential to distort the market.

RESULTS

This chapter discusses the outcome of the continuous growth model described in the previous chapter.

Results are calculated for two different demand scenarios:

- ***Minimum Demand:*** illustrates a deployment where demand density is never high enough for the network to achieve more than one subscriber per node. This is the maximally conservative scenario[86], corresponding to a "virtual" user density of 7.7%[87] with no demand growth. This scenario is significant because if the CWN model can be an attractive business with one user per node, the technical characteristics of wireless mesh allow the construction of viable infrastructure in areas with extremely low demand.
    - This scenario is depicted in the graphs with solid blue: ▬
- ***Typical Demand:*** illustrates a deployment with subscriber density and density growth according to the average national percentage of internet subscribers
    - This scenario is depicted in the graphs with outline red: ▭

With respect to our policy objective, our ideal outcome would be to make the CWN an attractive business in the minimum demand case; however, there is still an opportunity for CWNs to increase affordable access even if the minimum demand case is not attractive for the CWN. If the CWN can be profitable at any demand level below that which is profitable for carrier-class fixed-access, it adds value to the ecosystem by speeding the spread of affordable access.

The chapter begins with a discussion of the a base case model, which uses current conditions for Kenyan SSOs as inputs, then goes on to discuss the effects of modifying a variety of different inputs.

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[86] This is true because the cost to cover distances of up to 1km has almost no additional cost. As a result, the worst case "virtual" subscriber density for the network is 1/(households covered by a single access point).

[87] In our model we assume a 50m coverage radius for each AP and an area of 0.001km^2 yielding about 13 users covered per node. The area of 0.001km^2 corresponds to the approximate area of residential properties in Mt. View estate. Using the Mt. View assumption for footprint is conservative because, as a wealthier area, the average property size is relatively large. For more on the calculation of coverage radius see Appendix H.

After examining each input alone, the analysis will show that no single input can be altered sufficiently in isolation to make the case for the CWN at either demand level; however, a strategy that affects multiple variables can yield attractive results.

For each set of inputs described in this section, a graph will be shown depicting the evolution of operator debt as the network expands from 0 to 60 nodes. The graph will always be shown with the same Y scale and, with the exception of growth rate sensitivity discussion, the X scale (number of nodes) divided by 2 will always be equal to time in months[88].

Each graph will show a curve for HD and LD scenarios in their respective colors. On each curve, the locations of the critical points ***Cash-flow positive (C), Growth-sustainable (G)***[89] and ***Payback-period (P)*** will be called out. A table accompanying each graph will list the numeric values for these three critical points along with the peak debt incurred by the SSO.

Figure 5 is a representative example of the results output that will be used throughout this chapter. Each graph shows both the HD (outline red) and LD (solid blue) scenarios. In each graph, unbroken lines depict the variable case being discussed, while the dashed lines depict the base case with no node licensing (section 4.3.1) as comparison[90].

Any critical points *(C), (G), (P)* will be marked ***on the variable cases only,*** if they fall within the 24 month window that we have defined for our sustainability criteria. For instance, the HD variable case in Figure 5 shows all three critical points. Note that, of the three points, only *(G) and (P)* are easily identifiable from simply looking at the curves. *(G)* is the point at which *dy/dx* of the curve changes from positive to negative. *(P)* is the point where the curve crosses y=*0*. Point *(C)* is called out on the graphs for convenience, but does not correspond to an obvious feature in the curve.

Below each graph is a table of values. This table provides numerical outputs for the critical points in terms of both the number of nodes installed at the critical point and the time to reach the critical point. The table also provides a numerical value for *peak-debt*, which is the maximum *y* value of the curve (and corresponds to *(G)*). Values listed as *>72* (for nodes) or *>36* (for months) indicate that the critical point does not occur within the timeframe of our analysis. A value of *N/A* indicates that a critical point may never be reached.

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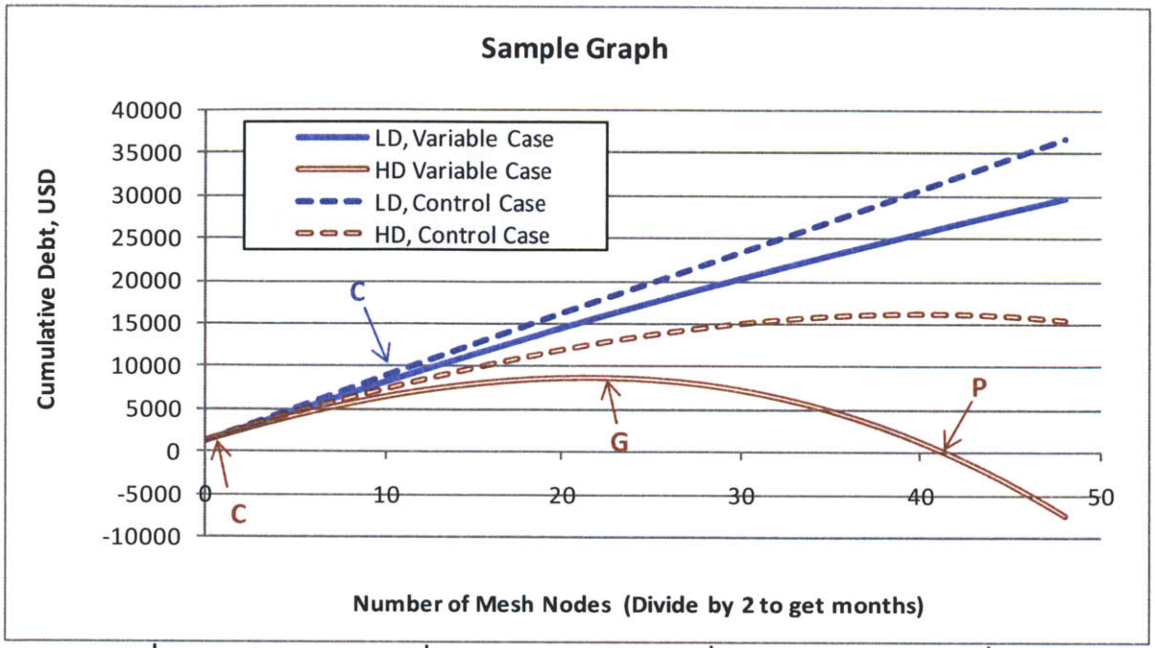
[88] Recall that the imposed growth rate is 2 nodes per month.

[89] The growth sustainable point also corresponds to the point of peak-debt.

[90] The base case (with licensing) is shown as a combination dot-dash line.



Demand Scenario	**Cash Positive** Nodes	Months	**Growth-Sustainable** Nodes	Months	**Debt Payback** Nodes	Months	**Peak-Debt**
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	5	2.5	>72	>36	>72	>36	N/A
HD	1	0.5	18	9	35	17.5	$7,058

FIGURE 5: SAMPLE RESULTS

Reminder: Because, as discussed in the methodology, it may not be necessary for operators to generate their income directly from the network for CWN operation to be attractive, the component of operator salary is discussed as a separate variable at the end of the results section (4.3.8). The rest of the examples look only at the cost for the system itself, excluding the operator.

BASE CASES

This section explores the two demand scenarios, as described in section 4, using the current conditions in the Nairobi area as inputs. These two scenarios will act as the baseline against which we compare policy interventions.

As discussed previously, the *minimum demand* (LD) scenario describes a situation where the network only ever attains one subscriber per node. This scenario would occur when total demand is less than 7.7% as described in section 4.

For the *typical demand* (HD) case, the model depends on CCK for estimated internet users. CCK estimates that roughly 20% of all Kenyans are internet users[91] (CCK 2011e). To make the most conservative estimate of potential subscribers per node, the model assumes at-most one subscription per household[92] and that any household contains all internet subscribers or no internet subscribers.

The base case assumes the following inputs:

Variable	HD	LD
Initial Demand, subscribers	1/node (= max 7.7%)	20% (= 2.6/node)
Demand Growth Rate	0%	35%
Node Coverage	0.013km^2	
Households / Node	13	
Cost / Node	$425	
Tower Rental / mo.	$500	
Maintenance, % CAPEX	2%	
Max Throughput (Access)	30Mbps	
Max Throughput (Backhaul)	60Mbps	
BHOL	100kbps	
Useful Rate	1024kbps	
Uplink, Cost / Mbps /mo.	$250	
License Fee / Node / yr.	$120	
Business License	$60	
Training	$550	
Interest Rate, APR	20%	
Installation Fee	$30	
Subscription Fee / mo.	$30	

TABLE 5: BASE CASE MODEL INPUTS

At step 0, the SSO decides to invest in a network. To do so, he must spend $550 in training, $60 on a business license, and slightly more than $600 on the equipment to make a long-link from a remote cellular tower to his location.

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[91] It is difficult to determine the accuracy of this number, but because we are considering the fringe around urban areas it is reasonable to assume that we would have an above-average density of internet users when compared to the country as a whole. We can use 2009 usage data for Nairobi county that claims more than 20% of inhabitants used the internet at least once a month as a sanity check (Apoyo Consultoria 2011, p.22).

[92] Average household sizes in Nairobi county range from 3-4 persons per household (Kenya Open Data Project 2011).

Based on the growth rate of 2 nodes per month, the model begins each new step after a time period of one-half month. All costs and revenues are assumed to come semi-monthly as well[93]

At step 1, the SSO purchases and deploys his first mesh node. This requires $425 for the purchase of the node and $120 to license the node for the first year. The SSO must also pay rental costs for the his space on the cellular tower, equivalent to one-half the total rental cost, as well as interest costs ($9) on all of the debt accumulated in step 0 ($1223). Finally, the SSO must pay for enough uplink bandwidth to serve all of his subscribers ($125 for LD, $275 for HD). The SSO then generates installation fees for each new subscriber and one-half month worth of subscription fees.

At step 2, the operator purchases, licenses and installs a second mesh node, pays interest on debt, buys more bandwidth, collects installation fees from new users, and subscription fees from all users. Additionally, he now pays the equivalent of 2% APR maintenance costs for all of the nodes deployed in previous steps.

An example output balance sheet for the first five steps of an example run is shown in Table 1 on page 30

As the network grows the SSO gains two important advantages. First, network level recurring costs such as tower rental are spread among more users. Second, bandwidth can be more effectively over-subscribed as the user base grows.

Because of the scaling advantages, a network with a favorable set of initial conditions will eventually generate sufficient revenue to cover the cost of continued expansion and begin paying back accumulated debt. This occurs eventually in the HD base case, but too far off in time to be shown on the graph in Figure 6. This never occurs in the base case for the LD network because of the effect of interest on debt.

While the network gains some benefits of scale from expansion, it also initially accumulates debt for the operator. With an unfavorable set of initial conditions, the cost of this debt can easily overwhelm the SSO, making him unable to recover his debts from revenue. This occurs in the LD base case.

Figure 6 illustrates the accumulated debt of the SSO for the LD and HD scenario as he expands his CWN, using the format described in the beginning of section 4.

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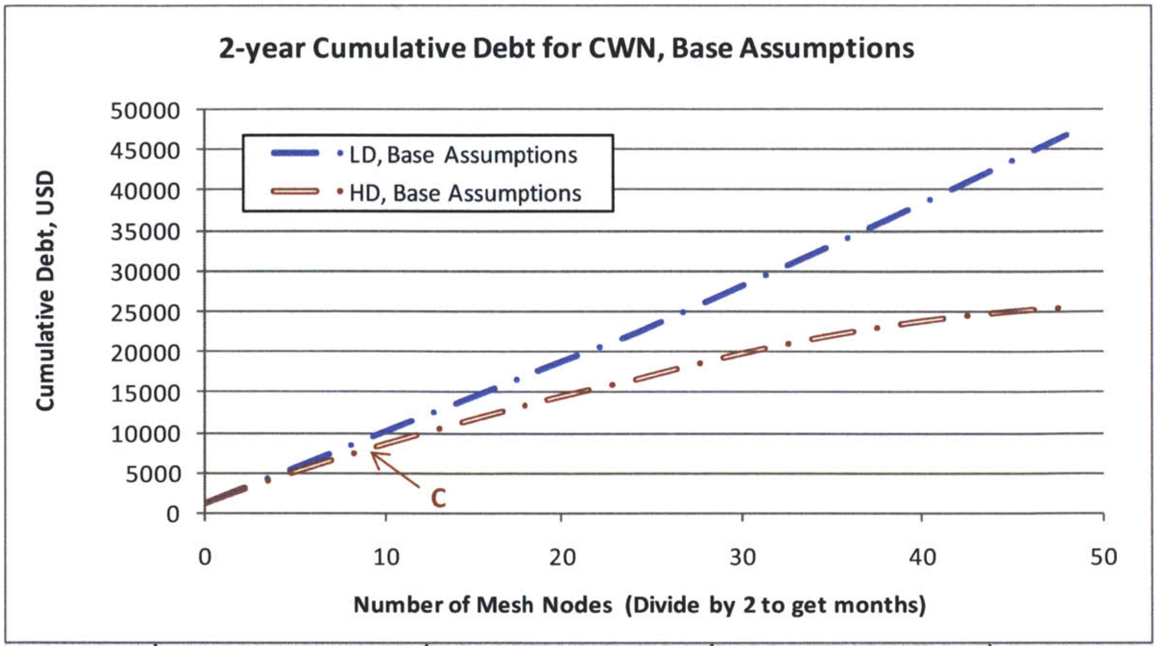
[93] The assumption for semi-monthly payments is conservative compared to up-front monthly payments, which is the expected payment method.



Demand	**Cash Positive**		**Growth-Sustainable**		**Debt Payback**		
Scenario	Nodes	Months	Nodes	Months	Nodes	Months	**Peak-Debt**
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HD	9	4.5	59	29.5	>72	>36	$27,149

FIGURE 6: BASE CASE CUMULATIVE DEBT FOR THE CWN

Figure 7 breaks down the total costs and revenues for the base case:

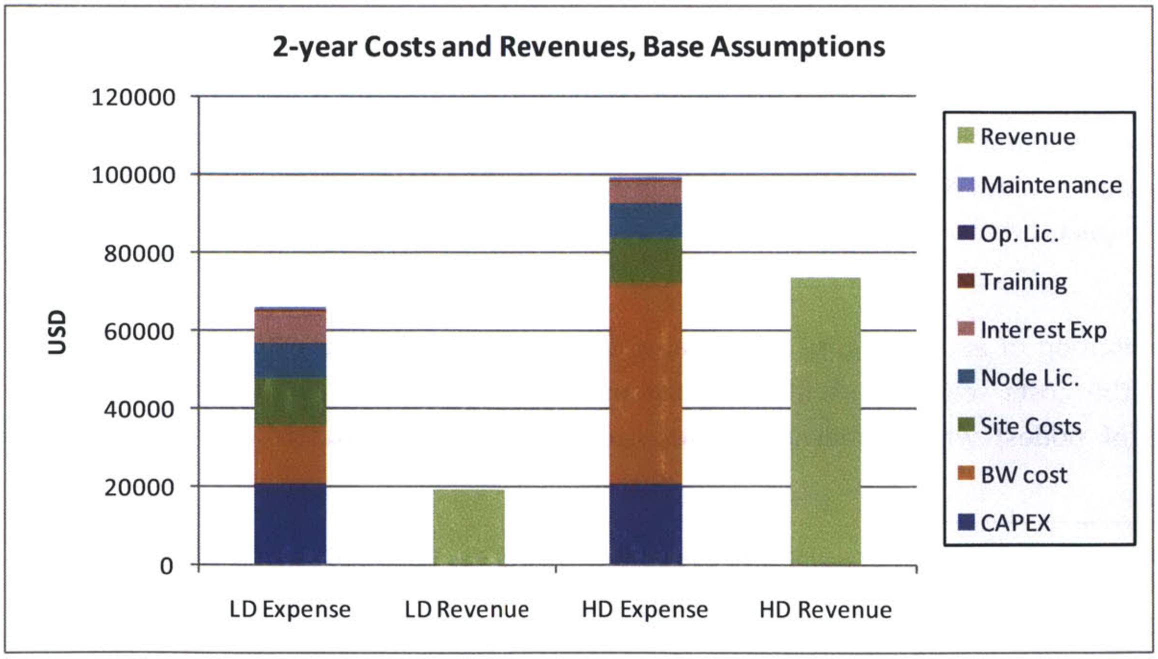


FIGURE 7: TWO YEAR COST BREAKDOWN FOR THE CWN AT DIFFERENT PENETRATION RATES

The key factor to observe from the base case is that neither the HD nor the LD scenario presents an attractive business case to the SSO. In the LD scenario, the SSO is overwhelmed with debt and never becomes sustainable. In the HD case, the SSO eventually does achieve sustainable growth, but not before scaling to more than 59 nodes. This scale would take more than 29 months to achieve. Such a large scale at (and corresponding long time period to) sustainable growth leaves the operator open to a very large financial risk (>$27k), and requires assurance that the CWM business will remain relevant for many years[94] before paying off its debt.

IMPACT BY COST CATEGORY

When attempting to modify the outcome of CWN deployment by modifying the SSO's input costs, not all cost categories are created equal. The amount any one cost category can change the outcome for the SSO is affected by a variety of factors, including:

- The fraction of total costs that are attributable to the cost category
- When in time the costs in the category occur
- How the costs in the category scale with growth[95]
- How much of a change in the input a policy is able to affect in the cost category

All else equal, cost categories that are larger contributors to the total have a greater impact for the same percentage change in input. Of two equal cost contributors, the category that accrues its costs more quickly in the evolution of the business will have greater impact because excess costs must be covered by borrowing, which incurs interest.

The contribution of each category to cost also depends on the total user density, and many of the costs scale differently. For instance, hardware cost scales in coverage (number of nodes) while bandwidth costs scale in number of subscribers. Thus,

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[94] Our model only ran for three years, and at that point the network was near its peak debt. We would estimate that it would take at least 5 years for the network to be debt-free. This is risky both because of the rapidly evolving market and the potential that this time period would begin to reach the limits of useful lifetime for the hardware.

[95] Some costs do not scale with the network, other scale with the number of nodes, other scale with the number of users, etc. Also, some costs may scale linearly while others may not.

bandwidth will make a greater proportional contribution to costs for a site with greater demand density.

For any given demand scenario, we can use the concept of elasticity, as described in Equation 8, to compare the sensitivity of the system to changes in each cost category. The elasticity measures the ratio of the fractional change in system cost to a fractional change in the amount of any particular input cost. By choosing a common percentage reduction in cost across all categories we can use the elasticity to directly compare the impact of comparable price changes in each category.

$$E_c = \frac{\%\,\textbf{\textit{reduction in total cost of the CWN over 2 years}}}{\%\,\textbf{\textit{reduction in category cost over two years}}} \qquad \textbf{8.}$$

Table 6 shows elasticity values for each of the cost categories from Figure 7 in response to a 20% (0.2) change in input costs.

Elasticities by Category
for 20% Cost Reduction

	Scenario	
Category	LD	HD
CAPEX	0.385	0.256
Training	0.060	0.008
Site Costs	0.219	0.145
Op. Lic.	0.001	0.001
Node. Lic	0.153	0.101
Bandwidth	0.262	0.576
Interest	0.129	0.059

TABLE 6: SYSTEM COST ELASTICITIES FOR COST REDUCTIONS BY CATEGORY

The elasticity metric provides an effective "first-pass" method of identifying which cost categories are the best targets for cost reduction in a particular scenario. For instance, the LD scenario is most sensitive to changes in the cost of hardware (CAPEX), while in the HD scenario, bandwidth is most important.

In a real policy environment, however, simple elasticity is only one part of the picture. This is because not all costs are equally easy to control. For instance, the regulator might easily eliminate a licensing fee, but would have more difficulty controlling the price of wireless hardware. Interventions with the highest impact are those that affect categories having both a high elasticity to input changes and inputs with large price responses to policy interventions. We can compare impact abstractly for each category by multiplying the elasticity from Table 6 and the fractional cost reduction (*M)* that can be affected in the category's input cost by policy intervention[96]. Equation 9 describes the Impact coefficient:

$$I = E_c * M_c \qquad \textbf{9.}$$

Comparing Site Costs and CAPEX provides an illustration of how a category with a greater elasticity can have a greater impact than one with a lower elasticity based on the responsiveness of the inputs to policy intervention. In the HD scenario, the system is more elastic to CAPEX (0.256) than to Site Costs (0.145); however, as described in section 4.3.4 and 4.3.5, we expect policy intervention to decrease site costs by 90% from their original cost through policy intervention while only decreasing CAPEX by 30% from its original cost. Because of the large reduction in the input variable for Site Costs, this category has more impact (0.145 * 0.9 = 0.131) than CAPEX (0.256 * 0.3 = .077). This result is borne out in the faster achievement of critical values for a Site Cost intervention, as described in 4.3.4 and 4.3.5. Table 7 shows the impact coefficients for each cost category. Specific values of *M* are discussed in section 4.3.

Impact Coefficients by Category

		Scenario	
Category	M	LD	HD
CAPEX	0.3	0.116	0.077
Training	1.0	0.060	0.008
Site Costs	0.9	0.197	0.131
Op. Lic.	0.0	0.000	0.000
Node. Lic	1.0	0.153	0.101
Bandwidth @$150/Mbps	0.4	0.105	0.231
Bandwidth @$100/Mbps	0.6	0.157	0.346
Interest	0.6	0.078	0.036

TABLE 7: IMPACT COEFFICIENTS BY CATEGORY

A final consideration that is not explicitly captured in the metrics from Equations 8 and 9 is how costs scale with respect to subscriber growth, network growth and time. For instance, an intervention in the category of Bandwidth (@$100/Mbps) and one in CAPEX have very similar *I* values in the LD case in Table 6 (and therefore, a similar impact on 2-year cost), but because the underlying cost of purchasing a node is a one-time event while bandwidth costs are recurring, an intervention that targets the latter has a much greater long-term impact on the operation of the network. The following section (4.3) discusses the top five of the above categories in more detail, including the issue of scaling.

---

[96] For example, if bandwidth initially costs $250/Mbps and a policy intervention is able to reduce this cost to $100/Mbps (a 60% reduction), the *M* value for the Bandwidth cost category is 0.6.

The assumptions in the base model reflect the fact that the CWN is simply not large enough to achieve any leverage in the broadband marketplace; CWNs pay retail prices for products and service, and the "quantize-able" units of inputs such as tower space and network nodes are often sub-optimally large for their purposes. As it turns out, controlling the input of any single cost category is not sufficient to make a viable case for the CWN. Ultimately, a successful policy solution will require a combined intervention that reduces multiple costs.

The following subsections (4.3.1-4.3.9) detail the effects of each cost on the system and what reductions might be possible in each category through policy change.

LICENSE FEES

- *Impact coefficient:* ***LD=0.15; HD=0.10***
- *Scales With:* ***Coverage***
- *Cost is:* ***Recurring***

While per-node licensing only takes third position in terms of cost contribution over the first two years of CWN operation, it is perhaps the most detrimental to the LD business case. Like node hardware the licensing fees scale with coverage, but unlike CAPEX, the cost is unlikely to fall in time because it is a recurring annual cost per node.

If enforced[97], a per-node licensing requirement of \$120/yr accounts for a third of the monthly subscription costs for a CWN when nodes only have single users. No LD network could ever be sustainable if this fee applies. It must be eliminated or altered for the CWN to exist. As of 2003, both the US and EU recommend the license-free use of these bands, which is generally considered necessary for the viability of WiFi infrastructure (Best 2003)(Galperin 2005). ***The balance of the analysis below will assume that the per-node licensing fee is eliminated***. We believe this is politically tenable as CCK's recent gap analysis recommends similar fee waivers for mobile operators who build in under-served areas (Apoyo Consultoria 2011, pp.66–67).

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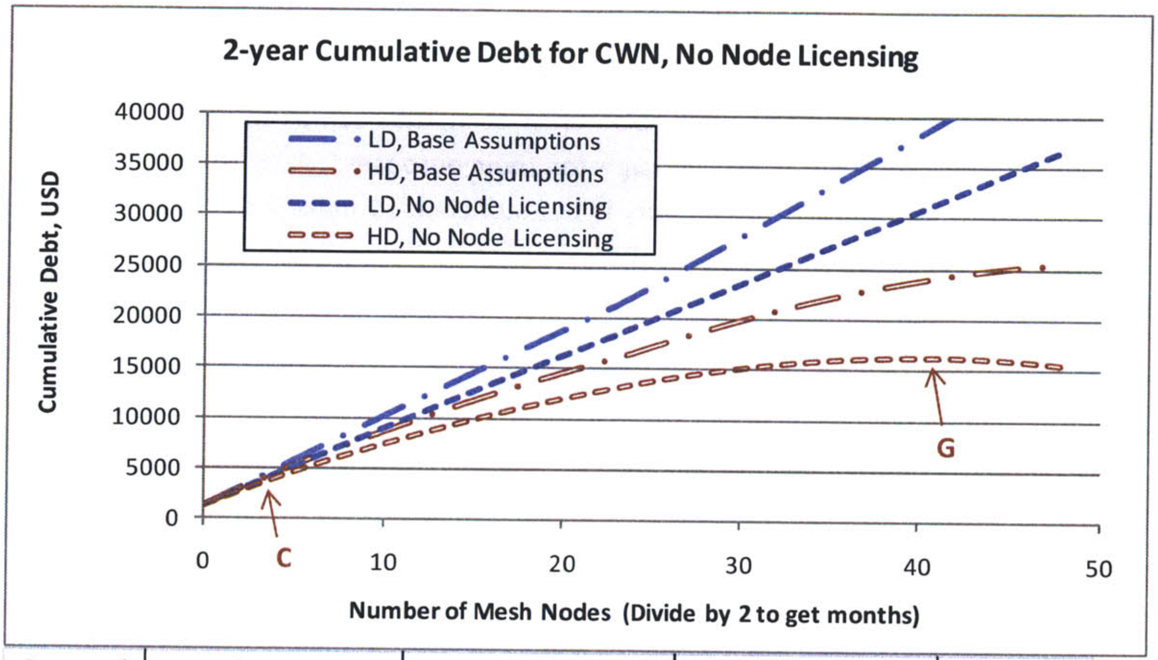
[97] As the reader may remember from section 3.2.6, none of our conversations with regulatory officials broached the subject of this fee, and we suspect that it would not be enforced for a distributed network such as the one discussed here.

By eliminating the fee alone, the HD case is able to grow sustainably from revenue after 41 nodes. The LD case still fails to converge even after eliminating the fee, as shown in Figure 8.



Demand Scenario	Cash Positive		Growth-Sustainable		Debt Payback		
	Nodes	Months	Nodes	Months	Nodes	Months	**Peak-Debt**
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HD	3	1.5	41	20.5	>72	>36	$16,186

FIGURE 8: DEBT LOAD WITHOUT NODE LICENSING

In all subsequent graphs, the dashed curves (such as those corresponding to HD and LD with no node licensing in Figure 8) will be included for visual comparison of the impact of modifying each input.

WHOLESALE BANDWIDTH

- *Impact coefficient @$100/Mbps:* ***LD=0.11, HD=0.23;***
- *Impact coefficient @$150/Mbps:* ***LD=0.16, HD=0.35***[98]
- *Scales With:* ***Users***
- *Cost is:* ***Recurring***

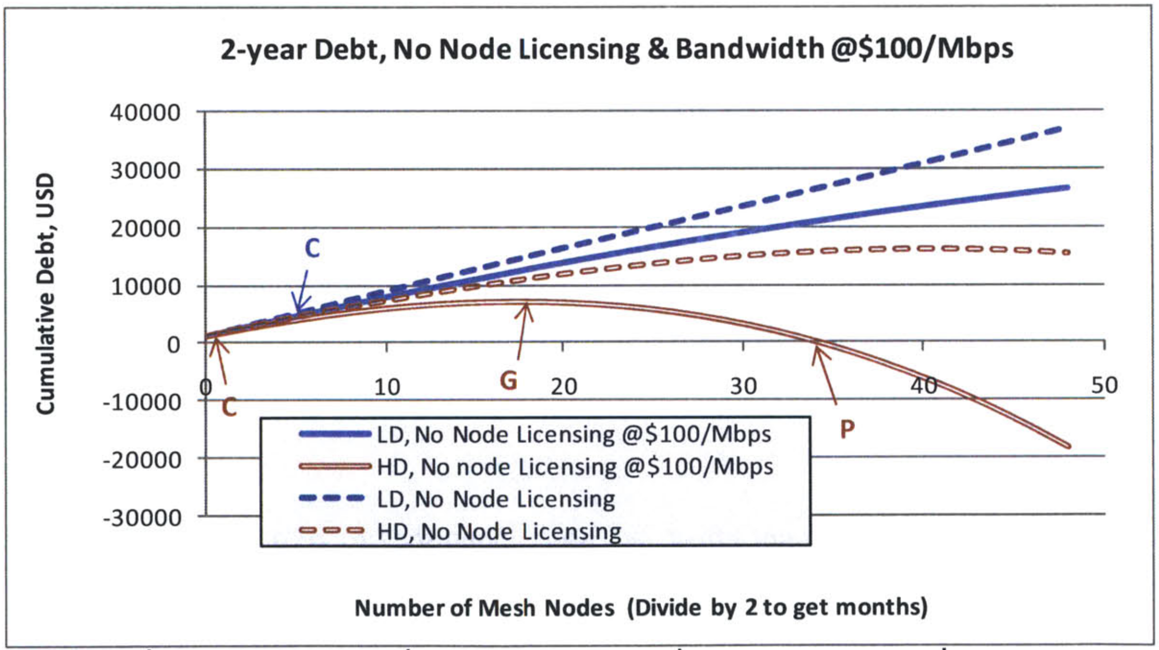
---

[98] A point of clarification on the *I* values for the two different bandwidth costs listed: The *I* value for the lower cost ($100/Mbps) is greater because the cost reduction from the base case is greater. In other words, the $100/Mbps case has a higher *M* (recall from section 4.2 that *M* is equal to the fractional reduction in input costs for any cost category).

Because over-subscription of bandwidth depends on a large user base, bandwidth costs are particularly acute for the CWN at the outset; however, because bandwidth needs scale with the number of users, bandwidth costs make up a much larger component of the cost for more densely subscribed networks. In both the HD and LD cases bandwidth is a major cost contributor and decreasing its cost has a major system impact.

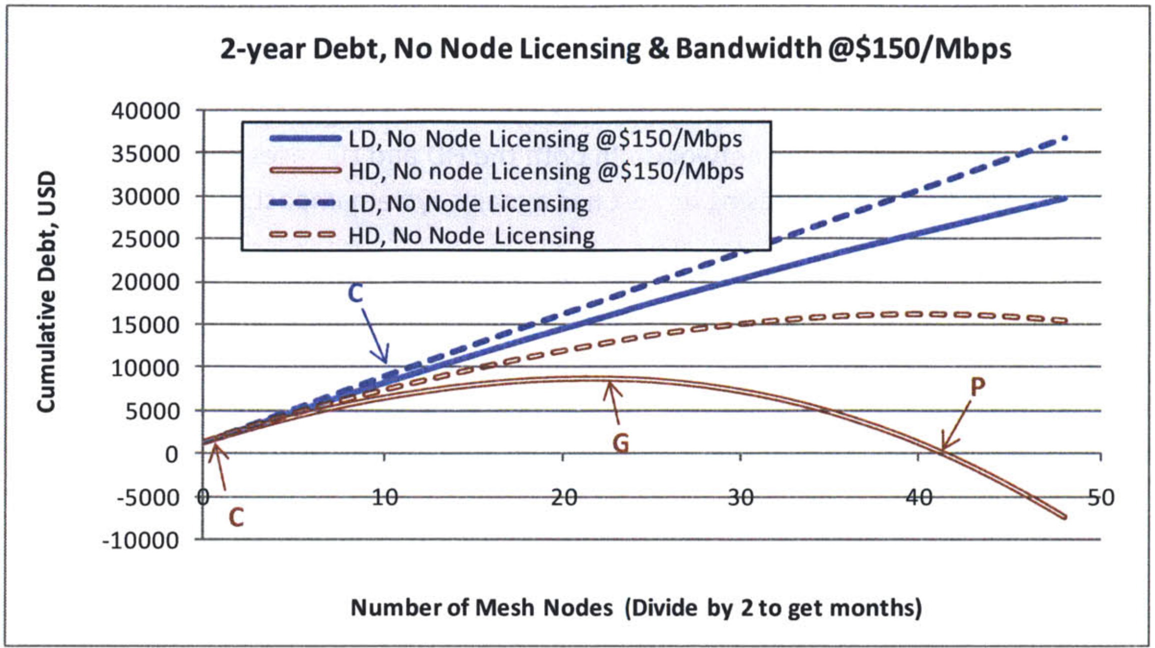
The base case assumes a price of $250/Mbps for dedicated capacity. This is a competitive retail price for dedicated bandwidth, but considerably more expensive than its underlying cost. For example, KENET, Kenya's educational and research AS, transits traffic from an exchange point in London to Nairobi at a cost of approximately $135/Mbps before overhead. Local traffic is virtually free, due to the existence of KIXP.

If even a modest amount of internet traffic remains in Kenya, a wholesale price for capacity could be as little as $100/Mbps. Not surprisingly, such decrease in price would be advantageous for both HD land LD scenarios. The graphs below show the HD and LD with capacity prices of $100 and $150/Mbps:



Demand	Cash Positive		Growth-Sustainable		Debt Payback		
Scenario	Nodes	Months	Nodes	Months	Nodes	Months	Peak-Debt
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	5	2.5	>72	>36	>72	>36	N/A
HD	1	0.5	18	9	35	17.5	$7,058

FIGURE 9: LOAD WITH WHOLESALE BANDWIDTH @$100/Mbps



Demand	Cash Positive		Growth-Sustainable		Debt Payback		
Scenario	Nodes	Months	Nodes	Months	Nodes	Months	Peak-Debt
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	10	5	>72	>36	>72	>36	N/A
HD	1	0.5	22	11	42	21	$8,628

FIGURE 10: DEBT LOAD WITH WHOLESALE BANDWIDTH @$150/Mbps

Combining license fee elimination and bandwidth cost reduction (at either level) meets two of our viability criteria (growth-sustainable in 1 year, full payback in 2 years) in the HD case, but still requires too high a debt as compared to the operator's income.

SHARED BANDWIDTH

- Impact Coefficient: ***N/A***[99]
- *Scales With:* ***None*** *(additional effect per user diminishes to zero as network scales)*

Recalling the scaling of contention ratios discussed in the previous section (4.3.2), additional savings are available if the operator is able to contend bandwidth like a large operator from the outset. In a situation where multiple SSOs are connecting to the core from the same tower, this is relatively simple to do and provides savings when the CWN is smallest and most vulnerable. For the LD scenario at $150/Mbps, sharing bandwidth

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[99] Unlike the other interventions, which simply scale cost inputs, the shared bandwidth intervention changes the shape of the bandwidth cost function. Thus, the *I* metric does not apply.

shifts the cash-positive point from month 5 to month 1. Tables 5 and 6 show the results of bandwidth sharing at $100/Mbps and $150/Mbps, respectively.

Demand	**Cash Positive**		**Growth-Sustainable**		**Debt Payback**		
Scenario	Nodes	Months	Nodes	Months	Nodes	Months	**Peak-Debt**
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	1	0.5	>72	>36	>72	>36	N/A
HD	1	0.5	18	9	34	17	$6,787

TABLE 8: PEAK-DEBT AND TIME TO CRITICAL POINTS WITH SHARED BANDWIDTH @$100/Mbps

Demand	**Cash Positive**		**Growth-Sustainable**		**Debt Payback**		
Scenario	Nodes	Months	Nodes	Months	Nodes	Months	**Peak-Debt**
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	1	0.5	>72	>36	>72	>36	N/A
HD	1	0.5	22	11	41	20.5	$8,188

TABLE 9: PEAK-DEBT AND TIME TO CRITICAL POINTS WITH SHARED BANDWIDTH @$150/Mbps

HARDWARE

- *Impact coefficient:* ***LD=0.12; HD=0.08***
- *Scales With:* ***Coverage (which is the same as users in the LD scenario)***
- *Cost is:* ***Fixed (for each new node)***

Hardware costs are the largest cost component in the LD scenario, and is particularly challenging in the LD scenario where we enforce that nodes only serve single subscribers. A straightforward way of decreasing costs for the SSO would be to provide them access to wholesale pricing on hardware. Unfortunately, the margin for decreasing the cost of hardware is smaller than for bandwidth, making the impact of intervention smaller[100]. The Figure 11 assumes the wholesale price as 70% of retail for the SSO. Under this assumption, neither the HD nor LD scenario meets our viability criteria when combined with only license fee elimination.

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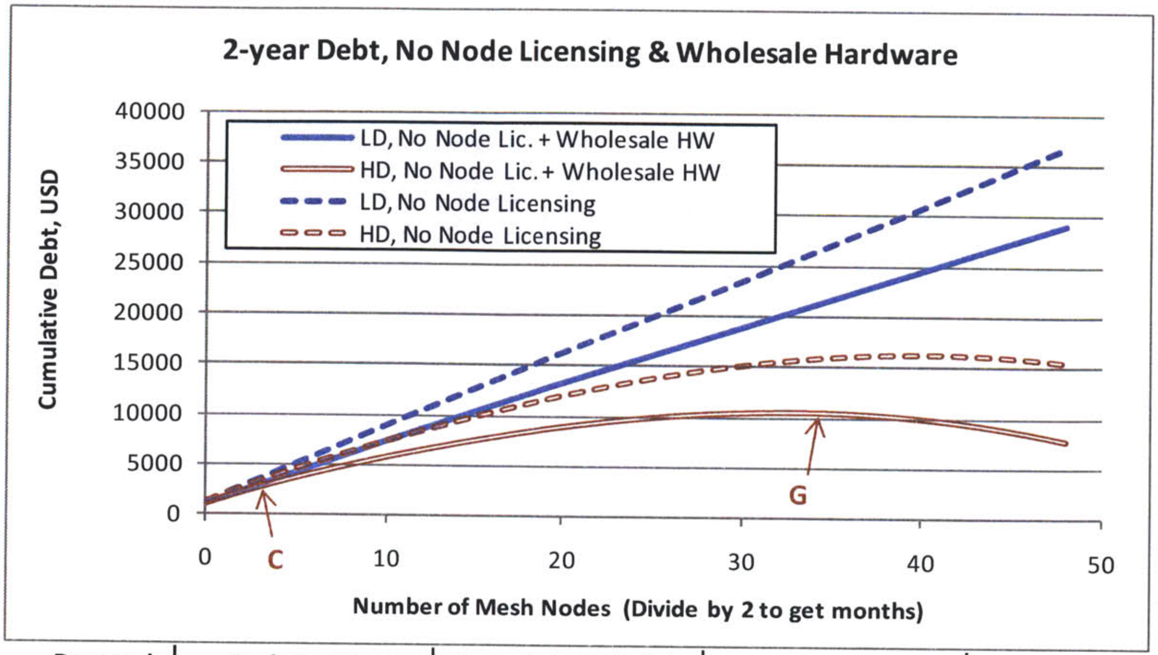
[100] Cost reduction fraction (*M)* for bandwidth is 0.4 or 0.6 for $150/Mbps or $100/Mbps, respectively, while the *M* for hardware is 0.3.



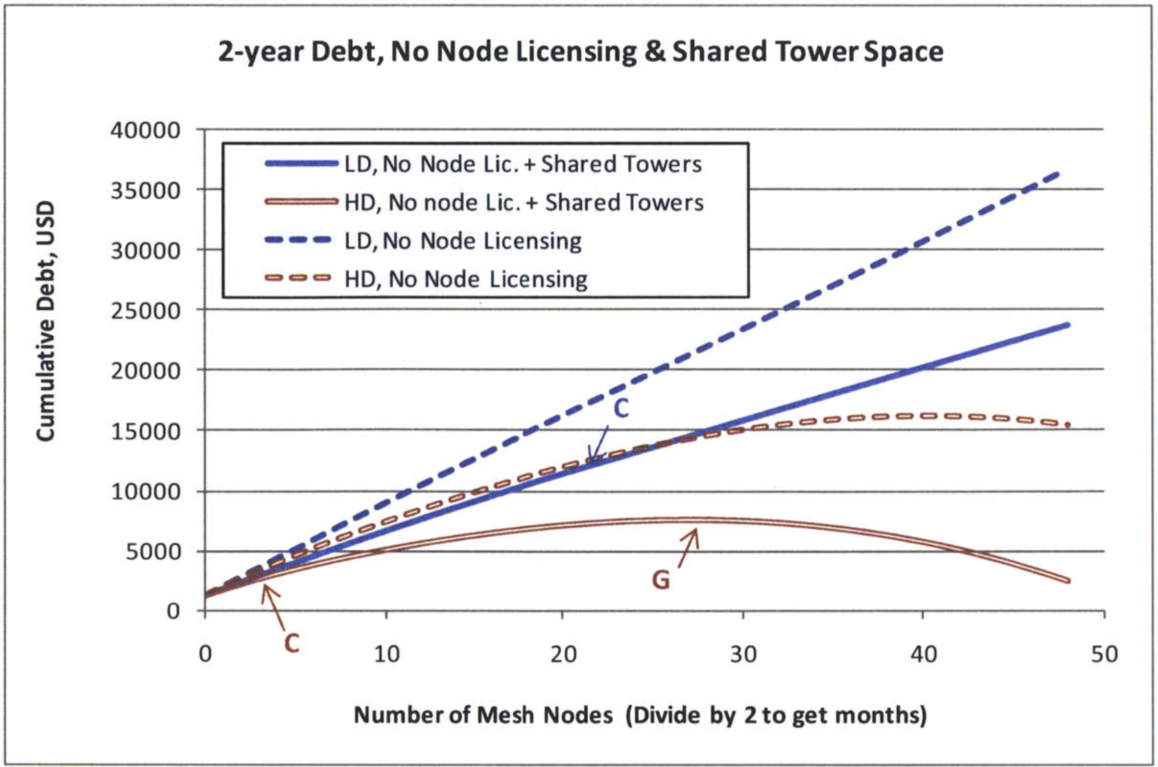
Demand	**Cash Positive**		**Growth-Sustainable**		**Debt Payback**		
Scenario	Nodes	Months	Nodes	Months	Nodes	Months	**Peak-Debt**
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HD	3	1.5	34	17	62	31	$10,599

FIGURE 11: DEBT LOAD WITH WHOLESALE HARDWARE

SITE COSTS

- *Impact coefficient:* ***LD=0.20; HD=0.13***
- *Scales With:* ***None***
- *Cost is:* ***Recurring***
- *Other:* ***Allows for shared bandwidth capacity***

A major advantage of the CWN is its low footprint in terms of power and space. This is an important benefit when siting equipment at individual residences, but less so when an individual SSO is trying to rent tower space, where the amount of capacity and equipment an individual CWN requires is not enough to justify the fees for renting tower space. Given the capacity required over two years of growth (in either the HD or LD scenario), a single tower could support 10 or more networks before consuming the available spectrum. If the small footprint of the individual CWN was exploited by backhauling multiple SSOs from the same tower, it would result in significant cost savings. The Figure 12 shows the result of 10:1 sharing of towers.



Demand Scenario	Cash Positive		Growth-Sustainable		Debt Payback		
	Nodes	Months	Nodes	Months	Nodes	Months	Peak-Debt
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	21	10.5	>72	>36	>72	>36	N/A
HD	3	1.5	28	14	53	26.5	$7,563

FIGURE 12: DEBT LOAD WITH TOWER SHARING

INTEREST RATES

- *Impact coefficient:* ***LD=0.08; HD=0.04***
- *Scales With:* ***Debt***
- *Cost is:* ***Recurring***

Because overall debt is relatively small, interest rates do not have a major effect on outcomes, even if the CWN were to achieve rates as low as major telecom providers (8%), which is less than half what they might obtain on their own. Interest rates are more than twice as important in the LD case as the HD, but in neither case is their impact alone significant.

COMBINED INTERVENTION

While no single variable can alone make the case for the LD CWN, a combined approach affecting all the variables discussed in section 4.3.1-4.3.6 looks much more attractive[101]. Figure 13 shows graphs of debt evolution for all interventions combined at bandwidth prices of $100/Mbps (A) and $150/Mbps (B) respectively. Inputs for this case are shown in Table 10 below:

Variable	HD & LD
Cost / Node	$297
Tower Rental / mo.	$50
Maintenance, % CAPEX	2%
Uplink, Cost / Mbps /mo.	$100 and $150
License Fee / Node / yr.	$0
Business License	$60
Training	$0
Intetrest Rate, APR	8%
Installation Fee	$30

TABLE 10: INPUT ASSUMTIONS FOR COMBINED INTERVENTION

If we assume the SSO derives his income indirectly from network operation, the HD scenario is well within our criteria for viability. The LD scenario still does not explicitly meet the criteria, but is finally beginning to look plausible, paying off all debt in just over 30 months.

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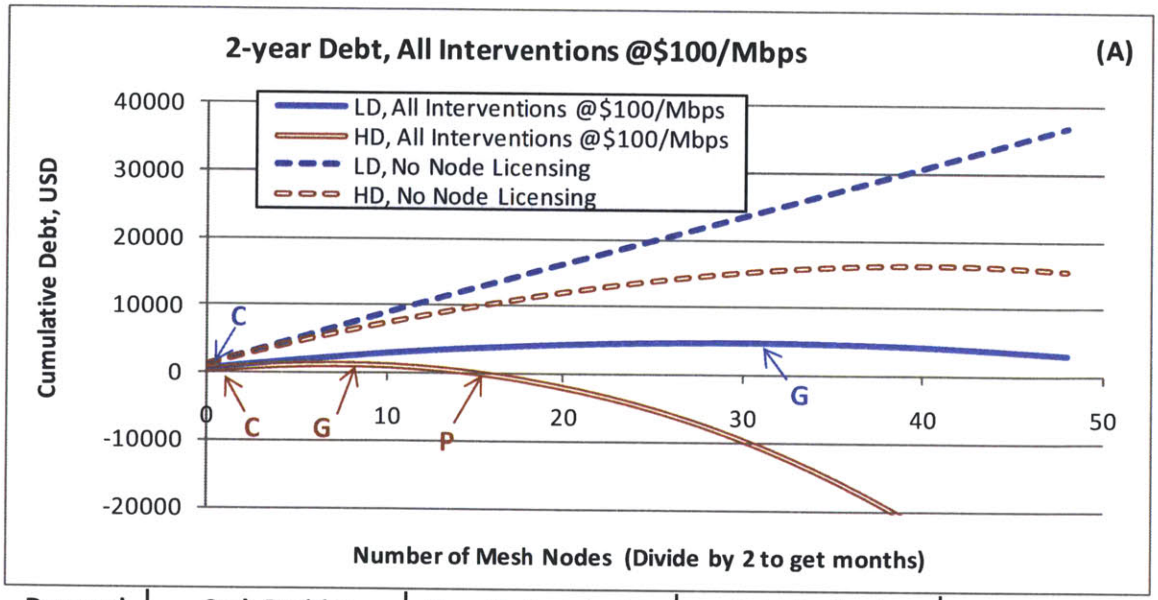
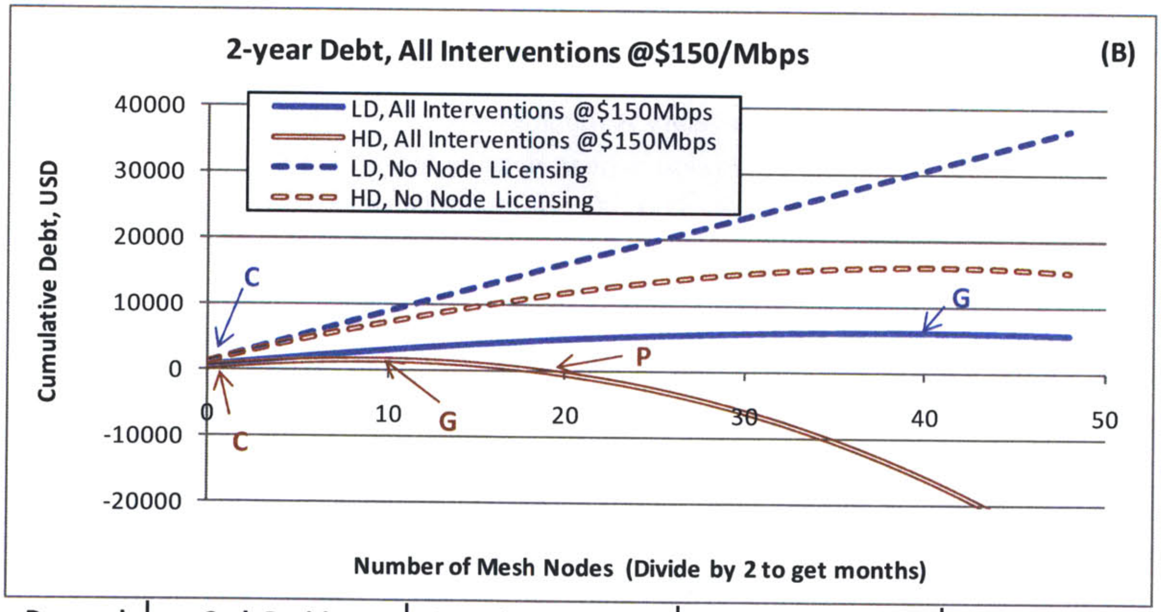
[101] The combined approach implements all the variable modifications discussed above as well as no-cost training.



Demand Scenario	Cash Positive		Growth-Sustainable		Debt Payback		
	Nodes	Months	Nodes	Months	Nodes	Months	Peak-Debt
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	1	0.5	31	15.5	61	30.5	$4,829
HD	1	0.5	8	4	16	8	$1,350



Demand Scenario	Cash Positive		Growth-Sustainable		Debt Payback		
	Nodes	Months	Nodes	Months	Nodes	Months	Peak-Debt
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	1	0.5	40	20	>73	>36	$6,197
HD	1	0.5	10	5	19	9.5	$1,581

FIGURE 13: DEBT LOAD WITH COMBINED INTERVENTIONS

COMBINED INTERVENTION, WITH SALARY

Once a profitable case has been made for the system in the absence of an operator, adding the requirement for operator salary simply shifts the scale at which the network becomes profitable and increases the peak debt incurred during early growth. Imposing the $200/mo. salary requirement on the combined intervention from above yields the following at $100/Mbps and $150/Mbps, respectively:

Demand	**Cash Positive**		**Growth-Sustainable**		**Debt Payback**		
Scenario	Nodes	Months	Nodes	Months	Nodes	Months	**Peak-Debt**
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	8	4	42	21	>72	>36	$8,545
HD	1	0.5	11	5.5	21	10.5	$2,224

TABLE 11: PEAK-DEBT AND CRITICAL POINTS WITH COMBINED INTERVENTION @$100/Mbps

Demand	**Cash Positive**		**Growth-Sustainable**		**Debt Payback**		
Scenario	Nodes	Months	Nodes	Months	Nodes	Months	**Peak-Debt**
Target	-	-	-	*12*	-	*24*	*$4,800*
LD	11	5.5	54	27	>72	>36	$11,140
HD	2	1	13	6.5	25	12.5	$2,662

TABLE 12: PEAK-DEBT AND CRITICAL POINTS WITH COMBINED INTERVENTION @$150/Mbps

Not surprisingly, the burden of adding a salary is much greater for LD than HD. In the $100/Mbps case, adding a salary to LD increases peak-debt by more than $3,700, while the HD scenario is changed by less than $1,000. At both bandwidth costs, the HD case still meets the viability criteria, while the LD cases fails to meet the requirements at both prices.

A reasonable criticism at this stage might be "how can we implement ALL of this?" As discussed later, I believe a model exists to do just that; however, as might be gleaned from our *I* values, some interventions can be omitted without fundamentally altering the outcome for the CWN in the HD case (the LD case is still challenging even with all interventions). Focusing on the HD case, using base case interest rates and full-cost training still yields a result that meets sustainability criteria @$100/Mbps, and nearly meets criteria at $150/Mbps. Results for this scenario are shown in Table 13.

Demand Scenario	Cash Positive		Growth-Sustainable		Debt Payback		
	Nodes	Months	Nodes	Months	Nodes	Months	Peak-Debt
Target	-	-	-	*12*	-	*24*	*$4,800*
HD @$100/Mbps	2	1	11	5.5	23	11.5	$2,833
HD @$150/Mbps	2	1	14	7	27	13.5	$3,320

TABLE 13: COMBINED INTERVENTION OMITTING TRAINING AND INTEREST COST REDUCTIONS

OPTIMIZING INITIAL SCALE

Until now, we have assumed a model where the SSO scales linearly from 0 to a size where the network can financially sustain growth. This corresponds to what we might expect from an individual with little access to capital and high aversion to risk, but what if we were to remove these restrictions?

Because a number of the network's costs, including operator salary, do not scale linearly with the network, starting the SSO at an initial scale greater than 1 node can be an advantage in terms of peak-debt and time to sustainability. For the LD case, rapidly installing 14 nodes in the first 2-week period[102] decreases the peak-debt of the operator by nearly $900 and decreases the time to debt payback to 33 months.

The sweet-spot of initial scale differs based on initial demand and bandwidth cost, as shown in Figure 14:

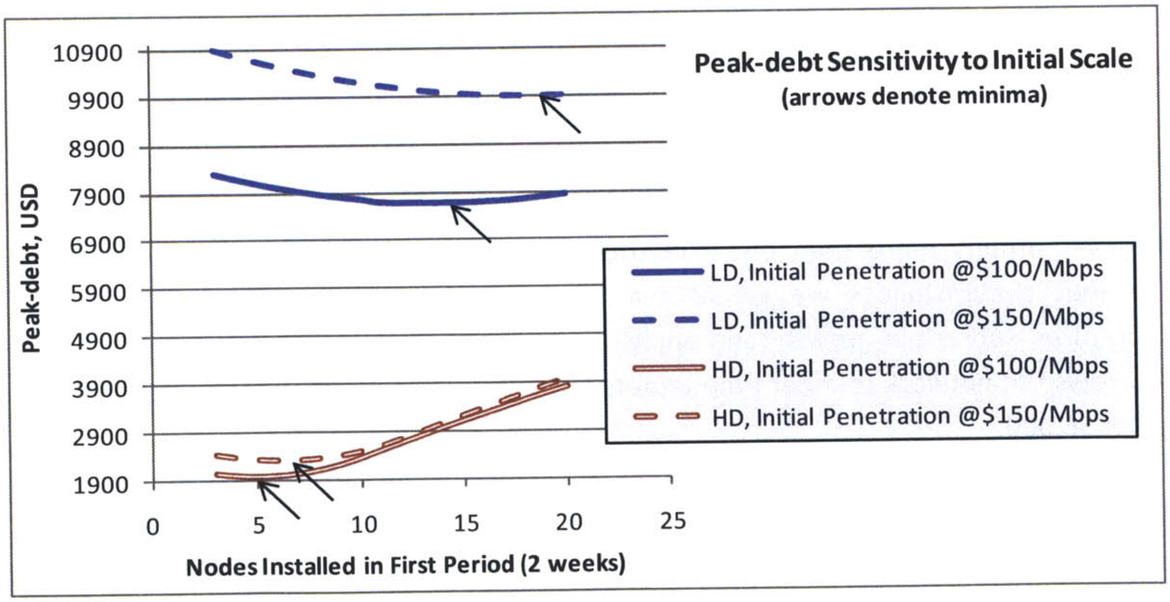


FIGURE 14: PEAK-DEBT SENSITIVITY TO INITIAL SCALE

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[102] Installing a mesh node in a day is not difficult; however, a plan of one installation per day would require that all the locations be pre-selected and installation appointments be made in advance.

Table 14 shows the best possible outcome for HD and LD scenarios with all interventions described in Table 10 at both bandwidth prices.

Demand Scenario	**Initial Scale, No. of Nodes**	**Growth-Sustainable** Nodes	Months	**Debt Payback** Nodes	Months	**Peak-Debt**
Target	-	-	*12*	-	*24*	*$4,800*
LD @$100/Mbps	14	41	14	79	33	$7,652
LD @$150/Mbps	18	54	18.5	>72	>36	$9,902
HD @$100/Mbps	5	11	3.5	20	8	$1,987
HD @$150/Mbps	7	13	3.5	25	9.5	$2,353

TABLE 14: PEAK-DEBT AND CRITICAL POINTS WITH OPTIMIZED INITIAL SCALE

SUMMARY

In the base case, the CWN model does not make an attractive business venture for the SSO, but this section has shown that there is considerable flexibility to improve the business conditions for the SSO by providing it access to competitive prices, lower interest rates and knowledge at no cost. The analysis has further shown that enabling the SSO to begin operations at a slightly larger scale can (non-intuitively) decrease the maximum amount of debt that he will incur as his network grows to sustainability.

Combining all interventions would make the scenario corresponding to typical demand density surrounding Nairobi very attractive as a business. Even with all interventions the Low Density scenario is feasible, but not particularly attractive; however, the way this scenario is structured in the model is maximally conservative. Enforcing that the network never attains more than one subscriber per mesh node is perhaps more restrictive that circumstances we would see in the field. Simply removing the assumption of no subscriber growth (and applying the 35% growth rate applied to the HD case) allows the network to meet time targets for sustainability, with a peak debt in the range of $6,000.

DISCUSSION

As discussed in the previous chapter, there is a set of plausible assumptions that make the CWN a viable small business; and this business, if implemented broadly, has the potential to reach many Kenyans who might otherwise wait years for affordable broadband services. The challenge for the Universal Service oriented regulator is enabling the SSO.

SSOs are very unlike incumbent operators—or well-funded new entrants—with traditional carrier-class systems. Unlike the incumbents, the capital and hardware operating costs of the deploying a CWN can be sustained in areas of low-demand; however, the CWN lacks access to the inexpensive capital, competitive pricing and specialized skilled labor that large commercial telecoms take for granted. A Universal Service Fund with a mandate to support infrastructure growth simply through "subsidies, loans and grants" (CCK 2010a) is perfectly well suited to expanding the reach of carrier class systems, but capital subsidies loans and grants are an incomplete solution when provided directly to individual CWNs, and operating subsidies are difficult to provide efficiently or a market neutral manner (discussed in 5.3 and 5.4).

Properly supporting CWN operators is not merely a matter of capital injection, but instead one of bolstering the CWNs leverage in the marketplace. Even with an application-appropriate technological solution and start-up funds, the SSO needs access to key inputs at competitive prices to provide affordable services. Access to this pricing is unlikely for the SSO in isolation. At the same time, the CWN model depends on the SSO for the goodwill and support of the community (such that it would be difficult for an outside commercial provider to implement the same model).

An effective approach to supporting the CWN creates the illusion of scale to the market while keeping the CWNs' local character intact. So, how might this get done?

THE CWN COOPERATIVE

While any individual CWN might be insignificant in the telecommunications marketplace, even a small success of the CWN model across multiple sites generates enough aggregate volume to increase the purchasing power of the group. Ten CWNs, for example, would purchase 100 wireless radios in the first month of business. By the end of a year they would purchase 750 radios and 23Mbps of dedicated capacity. If the group scaled to a hundred operators, the retail volume in radio hardware would make the group a major single buyer for even the larger low-cost WISP hardware manufacturers.

At sufficient scale, a community wireless cooperative (CWC) could also afford to become a government licensed network facilities provider[103]. In the short term, this allows for cost-based interconnection and protection from anti-competitive behavior. In the long term, a CWC puts the SSO on better bargaining footing as carrier-class networks begin to expand. In particular, the CWC will have a greater resource base to plan (or develop new technologies) for technological succession. On its own, no CWN would be able to afford to legitimize or protect itself in these ways.

The CWC can address a variety of the weaknesses of individual CWNs, as well as providing some advantages that are not available to other providers.

As discussed earlier, CWNs lack sufficient scale to in-source all the technical resources that might be necessary to address all types of failures effectively (Surana et al. 2008). This is both a knowledge and capital equipment problem. At the same time, the types of failures that are outside the expertise of the SSO are relatively infrequent. In the CWC, these specialized resources can be centralized and shared amongst operators. As the network operators become more independent and require less centralized technical support, central technical resources can focus increasingly on improving the networking platform with community feedback[104].

Another benefit of a centralized organization is the ability to create standards, cross-compatibility and a recognizable brand. Standards both put pressure on the SSO to run a quality operation as well as give the central organization the ability to remotely identify and diagnose reliability problems. Cross-compatibility strengthens the organization by making many small networks behave as one. Taking a page from the

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[103] The lowest tier of network facilities provider costs a minimum of $2400/yr or 0.5% of revenue (CCK 2011a). At the scale of 100 CWNs, this cost would be negligible.

[104] This process follows the open-source model used successfully by system components such as OpenWRT and to a lesser extent by Ubiquiti. Hallmarks of success for this model are the generation of a large participatory user base and the creation of an environment that encourages users to contribute back to the core platform in progressively more trusted capacities over time. In this model, super-users, gurus and developers rise organically through the ranks of common users. This model applies directly to the CWC system of central support and platform development.

playbook of FON[105], centralized management could even enable customers of one network to access the internet through any SSO's system with automated allocation of subscription fees to operators based on usage.

A central organization could alleviate the financial burden on new operators by coordinating paid apprenticeship opportunities where new SSOs could generate income while learning from experienced operators in the field. Such an arrangement could also benefit the experienced SSOs by providing inexpensive skilled labor while helping new operators to learn the ropes.

Finally, the CWC could provide capital assistance in the form of low-interest loans for providers wanting to get started. This could be leveraged to let operators scale more quickly at the outset.

Because cash accounting is inherent to the provision of services, funding the cooperative's central services through a percentage of user subscription fees would be straightforward. In this approach, larger operators effectively subsidize central services for new operators. In return, the CWC might provide advantages to the SSOs such as territory management between SSOs in the CWC (so as to prevent harmful intra-organization) or providing means for SSOs to monetize the provision of backhaul to more remote CWNs through their infrastructure.

THE CASE FOR INTERVENTION

While the CWC seems to address the challenges inherent to the CWN, its creation represents a classic example of a coordination problem:

1. Participants must be geographically removed from each other to avoid competition, making them less likely to know each other initially;
2. Participants must take an initial financial risk to support the association;
3. The success of participants' investments depends partially on other participants with whom the investor has no relationship; and
4. Less successful participants are likely to receive a disproportionate share of the common resources[106].

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[105] La Fonera (aka FON) is a distributed access network where "Foneros" share their home WiFi with other FON users. The success of the model has resulted in millions of WiFi hostpots worldwide. http://corp.fon.com/us

These requirements create a series of barriers to CWC formation: Participants must first find each other; next build mutual trust; and only then would the risk associated with a cooperative venture be palatable. Even if such coming together were to occur organically, at least one participant would require the industry knowledge and connections to secure competitive vendor agreements and apply for relevant licenses. History shows that, even absent the explicit requirements for knowledge and connections, such partnerships rarely form without centralized coordination (Hollingsworth 1999, pp.25–26)

CCK, on the other hand, could seed this model with relative ease. Fully funding 10 SSOs and two young technical professionals to sustainable growth could cost as little as $50,000 and be fully repaid from operator revenue in twelve months[107] with continued revenue generation to support new operators.

This might seem like an obvious win to an objective observer, but those familiar with telecommunications are likely aware how much power incumbent operators have on government. These incumbents prefer that Universal Service funds continue to flow in their direction. The power of mobile operators, in particular (a group the CWN model would directly compete with), is very strong in Kenya. According to Bitange Ndemo of Kenya's ICT board[108], pressure from these operators delayed the levying of the universal service tax for two full years from the enactment of the law, as well as the decrease of the levy to 0.5% from the initially proposed maximum of 1%. It is also reasonable to suspect that mobile operators had a large say in the outcome of the *ICT Gap Analysis* oft-cited in this report, as it is almost entirely mobile-centric[109].

While there may be external pressure to keep USF infrastructure initiatives directed at incumbents, there is precedent within GoK for funding entrepreneurial ICT business (Vota 2011). Unfortunately, success has been mixed with such initiatives. KICTB's Pasha Program provides entrepreneurship training and 90% capital support to individuals opening community ICT centers that range from full-service computer training facilities

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[106] Due to the high cost of bandwidth, a more successful participant is likely to receive more total value even if he overpays for the shared resources such as technical support.

[107] This calculation assumes the organization funds 10 HD scenario operators to the level of their peak-debt ($2,353 at a bandwidth price of $150/Mbit). The CWC also employs three professionals at the level of $600/mo. and assumes 10% overhead for a total of 10*2353+14400+4513 = $49,643. The additional burden on each CWN to support the organization would be approximately $1900. This sum could be recovered from SSO income, extending the time to debt-payback for each CWN by 2 months to 11.5.

[108] Information provided in an in-person interview in August 2010.

[109] When I asked for the draft of this report prior to its recent release, I was also told by the assistant director of the Universal Service Program that there was a lot of pressure to release no information about it "until it had been reviewed by all the stakeholders". I was not told who those stakeholders were, but the one-sidedness of the results do much to narrow the field.

to simple cyber cafés. In addition to providing basic ICT services, these centers give users access to e-government and remote learning portals.

The Pasha model consists of two major components: initial training and capital access support. After Pasha operators receive their grants, they are largely set free from the funding organization, save for payment of loans. According to IBM's recent assessment of the Pasha Program, this hands-off approach has proved problematic. IBM identified the lack of standards, branding and a continuous support framework as key weaknesses of the Pasha model (Thraikill et al. 2010). An additional observation of the IBM team was the importance of reliable infrastructure to the success of the Pasha model; in particular, access to affordable internet connectivity (Murphy et al. 2010). Similar challenges were identified in CCK's pilot of school-based telecentres (CCK 2010b).

Modifying the entrepreneurial model to support an independent (non-profit) cooperative with a mandate to seed SSOs addresses the shortcomings of the direct grant approach because the organization is pressured to develop and support operators for its continued success and revenue. Adding a payment infrastructure component through CWCs further strengthens the model and provides a straightforward means of collecting income from members.

South Africa provides a recent example of a tightly integrated entrepreneurial model. Through its Innovation for Alleviation of Poverty Program, the government is piloting a CWN approach where wireless networks are used to build last-mile connectivity off of newly laid government fiber lines (Broadband 4 All 2009). In this model, SSOs are given free access to bandwidth in exchange for providing internet connectivity to schools and government offices. SSOs then profit by selling surplus bandwidth to private customers. By positioning government facilities on the ends of the links, an interest in continued success of the SSO is ensured. So far, the pilot has trained 19 local operators and connected 180 schools (Pandor 2010).

The AirJaldi project, originally seeded in close partnership with UC Berkeley's TIER, is another example of how access to core resources and connections in the nascent stage can lead to sustainable CWNs. AirJaldi now serves more than 10,000 customers in the lower Himalayas and is entirely self-sustainable. The organization has become a regional hub for rural WiFi expertise and runs regular training for a wide variety of participants (AirJaldi n.d.).

From a regulatory perspective, enabling a CWC also provides access to a rational means for extracting license fees from operators. Instead of the current fixed, per-device fee that disproportionally affects operators in low-density settings; the regulator could use

CWC revenues to extract an aggregate tax as a proportion of revenue, similar to that levied on commercial operators. This approach would allow the regulator to generate revenue while still enabling low-density deployments. Given the Kenya's relatively strict power requirements for unlicensed band radios[110], it is difficult to make a utility argument for individually licensing and tracking individual APs as the regulator currently desires, and current licensing regime is simply prohibitive to new growth.

FAIR COMPETITION AND MARKET NEUTRALITY

At first glance, the notion of specifically standing up an organization that supports CWNs may seem antithetical to the liberalized regulatory ideals of technology and market neutrality, but by employing the indirect approach described in Section 5.1, I argue it is quite the opposite.

While a liberalized telecommunications sector may not explicitly bar market entry for any company or technology[111], any particular market or regulatory regime may create entry barriers that effectively bar certain types of participants. In Kenya, for example, licensing fees and corporate structure requirements are onerous for very small operators, with a minimum one year buy-in of nearly $5000 and expectations of a full-fledged corporate entity. While it is possible for a SSO to operate as merely a consumer of network services, the operator then fails to be covered by regulations ensuring fair competition and can be easily priced out of existence by providers higher up in the supply chain. As the CWN model is not well-suited to a highly centralized corporate business model, it is unlikely that the mesh WiFi technology will gain mainstream traction in the marketplace without organizational support, despite its superiority for some applications. Standing up an independent and self-sustaining organization for CWNs gives the mesh model an opportunity to compete on a level playing field with other technologies without specifically subsidizing or taxing the use of any of the underlying technologies.

The approach of supporting CWNs through seed support of an operator's cooperative also avoids many of the pitfalls of incentives for universal service. Instead of artificially inserting a carrier-class solution into an environment that would otherwise not support it, supporting the CWC creates a distributed company with a competitive technology to

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[110] 1W E.I.R.P in the 2.4Ghz WiFi band, 4W in the 5Ghz band

[111] Assuming spectrum availability, which is a discussion outside of this paper's scope

enter the market on fair terms with other operators. Unlike subsidized commercial operators with carrier-class technology, the CWC must operate profitably in low-density areas in order to remain viable. Since the CWN is a more application-appropriate solution, it will operate at a lower cost and cover more areas profitably than other approaches.

The addition of another technology into the marketplace provides more differentiated services in areas of existing broadband coverage that could better serve some consumers. Unlicensed wireless networks may also have the potential to pressure local monopoly providers who try to gouge consumers in the last-mile[112].

COMPARISON OF APPROACHES

Because the CWC approach is market-based, it avoids many of the negative consequences of traditional regulation as well as providing a lower-cost method of service provision. Consider some other approaches:

1. Protect individual CWNs by imposing price controls on commercial operators and hardware vendors when selling to CWNs
2. Provide direct subsidies to users to buy internet connectivity at a higher price
3. Provide capital and operating subsidies to individual CWNs
4. Provide a capital subsidy to carrier-class operators to cover target areas

As one might imagine, the command-and-control method is the least expensive, but well-known to cause perverse incentives and cross-subsidies (Wilson 2000, pp.79–82), and given the wide variety of costs that would need controlling, it would effectively require the regulator to manage the entire market.

The method of direct subsidy is by far the most expensive, as it is both costly to implement, due to the requirement of interacting with each individual consumer, and guarantees the entire subsidy is consumed regardless of users' willingness to pay (users will obviously consume the subsidy before paying out of pocket). This method is, perhaps, market neutral, but gives higher cost technologies an advantage in areas

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[112] NetBlazr, Inc. (http://netblazr.com/) is a nascent example in Downtown Boston, MA of a WiFi ISP that serves corporate customers at 1/10th the cost of in-building fiber by bypassing a Verizon local-loop monopoly. Similar local-loop monopolies are likely to exist in Nairobi.

where they might not otherwise be able to compete against a CWN of equal market position.

Subsidizing individual CWNs directly is slightly less expensive than subsidizing users, but might provide perverse incentives to upstream providers who would prefer to capture the subsidy through inflated backhaul prices than to expand their own systems.

Subsidizing carrier-class systems effectively reinforces the status quo at cost, but fails to capture the savings associated with wireless mesh.

In contrast to these traditional approaches, seeding a cooperative CWN association is beneficial to free-market competition, while implementing a more cost-effective solution. Because the CWN technology is more appropriate for the application, CWNs are likely to generate a surplus that will make the CWC sustainable in the long term. Recalling our parameter space from Figure 1, it is likely that the CWN association approach is the only approach that sits solidly in the shaded area.

CONCLUSION

This thesis has demonstrated that the CWN model can be profitable in the case of low demand if it has access to competitive pricing from upstream bandwidth providers, tower providers and hardware vendors, as well as rationalized licensing costs from CCK. We suggest, from experience, that the SSO is unlikely to have access to the required competitive resources as an isolated entity, and that some outside intervention is needed.

We conclude that an effective approach to supporting the CWN is to seed a cooperative organization for CWN operators that could provide training, technical resources and capital support. We argue that this is a market neutral approach and has net benefit to the broadband market. This approach also integrates well with other ICT empowerment initiatives that GoK has already begun, and places the CWN in a better long-term position for technology succession.

While this analysis has been conducted for a specific set of values, it is important to understand that the challenge for the SSO is a structural one. While hardware and data capacity prices may decrease, these changes will occur throughout the marketplace, leaving the outlook for the CWN the same until its market position is improved.

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FUTURE WORK

MULTI-SITE WORK

While there are dozens of papers in the literature suggesting various models for the implementation of bottom-up infrastructure strategies, and many more describing isolated case studies, we were unable to find any examples where instances of any particular core model were replicated at more than one or two sites. There are likely a couple of reasons for this. The first is that much work in WiFi infrastructure is directed at isolated rural areas. This is, perhaps, not surprising, as these areas are challenging for scientists and glamorous for non-profits. Many times these sites are unique, and the model is very site-specific. A second reason is perhaps that the majority of low-cost ICT projects are only viable due to [initial] technical and financial support of outside entities, and as a result don't replicate themselves.

For the case of using WiFi infrastructure as a lead to carrier-class systems, a truly robust test of sustainability is whether or not a given model can be deployed beyond the means of a single village operator or research team. Until this occurs, it is difficult to determine the viability of making infrastructure construction accessible to "regular" people.

FOCUS ON DEVELOPMENT OF EMPOWERMENT PROGRAMS

As described earlier, most of the obstacles to success for the CWN come at the outset, particularly when it comes to training and support. Despite the importance of developing technically independent local operators, inadequate training is a common theme. To date, the literature contains no demonstration of a large-scale empowerment program where "ordinary" people are trained and supported through the process of building and running a CWN in a sustainable manner. Such programs must exist if the CWN model is to scale.

Developing such a program is a complex systems problem and not nearly as simple as it seems. In creating it, one must trade off the depth of knowledge of the new operator with the time investment required to develop that knowledge. To be sustainable, the system must be able to support new operator's gaps in knowledge as they begin implementation while providing them with the means to learn and grow such that they become independent over time.

STRATEGIES FOR CONVERGENCE AND TECHNOLOGICAL SUCCESSION

While bottom-up infrastructure projects in isolated rural areas can be reasonably secure when assuming 5-year payback periods and long-term safety from competition, the model of using WiFi as a rapid-expansion tool for high-performance networks must consider its competitive position much more quickly. As carrier-class networks expand, the CWNs on the fringe will face pressure, and be forced to evolve by either implementing their own carrier-class systems or by positioning themselves as a low-cost alternative (this second model is common with US WISPs).

A key direction of additional research is to understand the dynamics of this evolution. Provided that the CWN operates at a competitive scale and is protected from anti-competitive pricing, as we discuss in section 5.1, what is the likely outcome of encroachment by expanding carrier networks? Again, this is a complex issue. Already in Kenya we have heard of plays on the part of local communities to extract financial concessions from fixed-line operators building infrastructure (BiztechAfrica 2011). Will the existence of robust CWNs make it harder for fiber to be deployed? Will the CWN be a means to mitigate these challenges? More research is needed to find out.

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APPENDICES

APPENDIX A: MESH NODE BILL OF MATERIALS

		Double Radio		Triple Radio		Quad Radio		10km L-L		>10km L-L	
Component	Price	Qty	Subt.	Qty	Subt.	Qty	Subt.	Qty	Subt.	Qty	Subt.
NanoStationM5-Loco	$76	1	$76	2	$151	3	$227		$0		$0
PicoStationM2-HP	$89	1	$89	1	$89	1	$89		$0		$0
NanoBridgeM5 25	$118		$0		$0		$0		$0	2	$236
NanoBridgeM5 22	$89		$0		$0		$0	2	$178		$0
POE LVD charger	$50	1	$50	1	$50	1	$50	1	$50	1	$50
24V Pwr Supply w/surge	$21	1	$21	1	$21	1	$21	1	$21	1	$21
Ethernet Switch	$17		$0	1	$17	1	$17		$0		$0
Ethernet Cable (m)	$0	25	$6	30	$8	35	$9	32	$8	32	$8
Cable Ends	$3	4	$13	8	$26	10	$33	6	$20	6	$20
Mounting Pole	$14	1	$14	1	$14	1	$14		$0		$0
Mounting Bracket	$12	1	$12	1	$12	1	$12		$0		$0
Mounting Hardware	$6	1	$6	1	$6	1	$6		$0		$0
Enclosure	$3	1	$3	1	$3	1	$3	1	$3	1	$3
Battery	$9	2	$18	3	$27	4	$36	2	$18	2	$18
			$309		$425		$517		$298		$356

APPENDIX B: COST MODEL INPUT ASSUMPTIONS SUMMARY

Base Case:

Variable	HD	LD
Initial Demand, subscribers	1/node	20%
Demand Growth Rate	0	35%
Node Coverage	.013km^2	
Households / Node	13	
Cost / Node	$425	
Tower Rental / mo.	$500	
Maintenance, % CAPEX	2%	
Max Throughput (Access)	30Mbps	
Max Throughput (Backhaul)	60Mbps	
BHOL	100kbps	
Useful Rate	1024kbps	
Uplink, Cost / Mbps /mo.	$250	
License Fee / Node / yr.	$120	
Business License	$60	
Training	$550	
Interest Rate, APR	20%	
Installation Fee	$30	
Subscription Fee / mo.	$30	

Reduced Costs:

Variable	HD	LD
Cost / Node	$297	
Tower Rental / mo.	$50	
Maintenance, % CAPEX	2%	
Uplink, Cost / Mbps /mo.	$100 and $150	
License Fee / Node / yr.	$0	
Business License	$60	
Training	$0	
Interest Rate, APR	20%	
Installation Fee	$30	

APPENDIX C: BUSY HOUR OFFERED LOAD

BHOL is a measure of the average load a user tries to place on the network in the absence of congestion. This value is often used when calculating the capacity needed to serve a population of users as discussed in section 3.2.2. ADTRAN, inc. provides a detailed description and a method for calculating BHOL (2009) using the formula:

$$P = M\left(1 + \frac{r-1}{r+1}\right) \qquad 10.$$

Where:

P = the average load during peak periods (this is BHOL)

M = the long term average load, and

r = the diurnal max/min traffic ratio.

M and r can be found using the data from Cisco Visual Networking index.

ADTRAN estimates BHOL for US users at 95kbps for 2009, with an annual growth rate of 35%.

For Kenya, we lack the data to obtain M and r directly[113]; however we do know the estimated number of internet subscribers in Kenya and the total amount of international capacity available to act as a proxy. As discussed in Appendix D, CCK reports that Kenya's international connectivity is equivalent to 44kbps per internet subscriber. Given that most internet data traffic is still international, it would be difficult to believe a BHOL of more than double this number, even with local caching of static content. For the analysis in the paper we use a BHOL value of 100kbps.

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[113] The Visual Networking Index only provides aggregate statistics for the Middle East and Africa as a whole.

APPENDIX D: BROADBAND SERVICE AND INTERNET USE, KENYA

SERVICES AND PRICING

Investments in international broadband infrastructure have had disruptive effects on the Kenyan telecom economy. Over the course of only three years, the wholesale price of bandwidth has dropped one-hundred fold. Leaseholders on major international cables such as Seacom currently pay a marginal cost of about $25/Mbps. After amortization of IRUs, IP transit fees and domestic distribution costs, this bandwidth is likely reaching population centers such as Nairobi for between $100-$150Mbps/mo. As a point of comparison, this is ten times the competitive rate in Boston.

In terms of total connectivity, CCK reports Kenya's international capacity to be equivalent to 44kbps per internet subscriber. We know that a significant amount data is being served locally from both native Kenyan websites and from Google's global cache (Hernsman 2011); however, without knowing the total capacity dedicated to internet service in the country it is difficult to exactly determine the effective internet capacity per user.

While the baseline cost of providing data has decreased drastically, end-user pricing and access maintain a strong socio-economic and geographic bias. This is mainly a problem of the last mile. Even when broadband service is defined by data speeds of 256kbps and above, only 28% of the population and 3% of the geographic area in Kenya has access to broadband services. This service is overwhelmingly via mobile and concentrated around Nairobi (Apoyo Consultoria 2011, pp.38–52).

Despite the fact that Nairobi is by-far the most connected city in Kenya, affordable data services are still limited. A handful of commercial companies have begun to roll out high performance fixed broadband services to select neighborhoods within 10km of the city center. These networks provide residential customers with 1Mbps of unlimited data for as little as $12/mo, with up to 8Mbps for $60[114]. WiMax is also common, providing somewhat more geographical reach with prices competitive to fixed lines, but, according to Bitange Ndemo of Kenya's ICT board, these companies will frequently construct redundant infrastructure and compete with each other in the best markets rather than expand into riskier areas.

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[114] Assumes KES:USD exchange of 83:1.

Outside the urban core, fixed line and fixed wireless broadband services quickly become unavailable. Mobile data services do exist, but prices are considerably higher. Only three mobile providers in Kenya have 3G spectrum licenses (2 HSPA, 1 EV-DO) and only one provider in each upgrade path has significant coverage. Of these two, only Orange Telkom (EV-DO) provides unlimited broadband, at roughly $47/mo. Safaricom (HSPA) provides only metered service at broadband speeds, with rates ranging from approximately $0.04-$0.005/MB. Outside of urban areas, mobile systems also often fail to perform at broadband speeds, even by the conservative CCK definition of 256Kbps.

The following Table 15 provides example prices for data in the Nairobi area:

Approximate "Best" Prices for 1Mbps connection

Technology	Price	Notes
Mobile, HSPA	$0.005/MB	Metered connection. Unlimited plan is throttled to 128kbps
Mobile, EVDO	$47/mo.	
Fiber	$12/mo.	Offering is potentially price to entice users onto triple play.
ADSL	$80/mo.	Telkom offering, subtracting out the phone component.
WiMAX	$60/mo.	Was offered by Zuku, though now no longer on their website.

TABLE 15: EXAMPLE RESIDENTIAL INTERNET PRICES IN THE NAIROBI AREA

ACCESS AND USE

According to the latest CCK data, roughly one out of four Kenyans are active internet users. As of 2009, the last year for which we have comparative data, Kenya ranked 5th in Sub-Saharan Africa for internet penetration and 8th on the mainland continent. Since 2009, internet penetration in Kenya has increased nearly 150%. While Kenya has relatively high internet penetration in an African context, developed nations in North America, Europe and Asia have more than triple the users per capita (International Telecommunication Union 2011).

A key consideration in assessing the transformative potential of internet access in Kenya is how users access the internet. A user with always-on broadband service in his home that is billed at a flat rate will make different decisions about how to use the service than someone who pays by the megabyte (Anderson et al. 2002). Similarly, we might expect a person who has to walk to an internet café will use the internet differently than someone who has it on a device in his or her pocket. The full value of internet connectivity is realized when the barriers to using the internet as a resource are eliminated. Important considerations in this domain are cost, convenience, performance and access device capability.

Mobile data access—a method that accounts for 99% of Kenyan internet subscriptions (CCK 2011e)—is a mixed bag for barriers to use. Mobile data has the advantage of broad coverage and convenient access for dedicated mobile devices, but lacks flat-rate billing for all but the most expensive plans and has highly variable performance. For PC users, mobile data is also considerably less convenient, requiring an external modem that is rarely available for purchase outside of major cities, and the installation of dedicated software that users must use to log on and off as if they are using a fixed-line dial-up connection.

Cost aside, accessing the internet using a mobile phone—the most common method in Kenya—can be expected to adversely affect the breadth of use that one might expect over a broadband connection. Even with the most advanced smartphones over fast mobile connections, mobile devices are still treated by users as merely complementary to PCs (Nielsen & Fjuk 2010). Mobile phones are not a substitute for networked PCs.

When concerned with increasing use, not simply access, mobile subscription volume must also be viewed with a critical eye. Given that nearly all data consumption is prepaid, any data use by a user during a reporting period can be considered a "subscription", whether it was for 10MB or 10GB. As such, Kenyan mobile data "subscriptions" cannot automatically be assumed to indicate the same level of daily use that we might associate with mobile data users in developed countries on unlimited data contracts.

In all, it is likely that dependence on mobile data leads users to browse less and perform a narrower range of online tasks than we would otherwise expect from broadband subscribers, mitigating the transformative effect of broadband penetration and underscoring the need for other options.

Developed internet markets worldwide rely much less on mobile broadband than in today's nascent markets, especially African ones. Of the fifteen mainland African nations with broadband penetration greater than 1%, thirteen have mobile:fixed broadband subscription ratios greater than 5:1, nine have ratios greater than 10:1, five have ratios greater than 50:1 and three have ratios greater than 100:1. This stands in sharp contrast to developed internet markets where the ratio of mobile:fixed is almost universally less than 4:1[115]. Kenya has a mobile:fixed subscription ratio greater than 150:1 (International Telecommunication Union 2011).

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[115] With only two exceptions, countries with internet penetration greater than 50%, have mobile:fixed broadband ratios of 4:1 or less. Ratios are generated from raw ITU data (International Telecommunication Union 2011).

As the Kenyan market matures, one might expect the distribution of technologies to converge toward the developed market norm. Over the last two years this has, in fact, begun to occur. For the first time since the entry of mobile data, fixed broadband services are seeing higher subscription growth rates than mobile data services. Multiple operators now provide these services profitably in areas of high demand, but coverage is expanding very slowly outside of the most desirable markets.

APPENDIX E – UNIVERSAL SERVICE AND KENYA'S ACCESS GAPS

In the context of telecommunications policy, universal service is the concept of "promot[ing] the availability of quality services at just, reasonable and affordable rates for all consumers" (FCC 1996). The need for universal service policy is rooted in the simple truth that some customers—based geography, population density or other factors—are more expensive to reach with telecommunications infrastructure. For some of these customers, the fair price of serving them would be more than they are willing or able to pay.

Universal service was originally known in the context of universal service obligations, where monopoly telecommunication providers were obliged to provide telecommunication services in return for their monopoly status (or, alternately, the telecommunication company was state run, and the obligation for universal service was self-imposed).

With the rise of liberalized telecommunications, the need to compensate independent providers for expanding services into marginal markets became an important concern. Over the years, a variety of methods for accomplishing this have been attempted, with varying adverse consequences, until finally arriving at the concept of "Smart Subsidies" and "Universal Service Funds" (USF). In concept, this idea is relatively simple:

1. Presume that all telecommunications operators should share the financial burden of providing universal service.
2. Collect a tax on all operators equivalent to their share of the universal service burden
3. Offer up universal service funding to the lowest bidder willing to build in marginal areas.

According to ITU, a best practice USF targets subsidies to areas that will be operationally sustainable, but require initial capital support to be profitable. These areas are called "smart subsidy zones" (Blackman & Srivastava 2011, pp.157–158).

Kenya's recent *Study on ICT Access Gaps in Kenya* suggests use of the USF and modified Smart subsidy model, in a three-tiered strategy, with increasing subsidies and associated entry barriers for each tier. The proposed technological approach is extremely mobile-centric, to the degree that mobile data is simply assumed as the solution to the universal access problem[116].

The first tier of the study's recommendations for supporting universal service (as this paper's analysis for WiFi suggests is essential) suggests waiving spectrum fees for operators offering to build in identified gap areas. This is of little or no cost to the regulator in the short-term because the regulator would not collect these fees in the absence of infrastructure, and a potential increase in operator revenue stands to generate additional licensing fees for the regulator in the future.

The second tier invites operators to submit plans for serving gap areas that require a direct subsidy in addition to the spectrum fee waiver. These plans would need to be accepted by the operator and, in the event of multiple plans, competed for lowest cost.

For the least profitable projects, the regulator would design and auction infrastructure projects to the lowest bidder (Apoyo Consultoria 2011).

Small details aside, this approach is largely in line with the ITU documentation on universal service with the exception that it makes no provision for small scale operations or alternative technologies (or even technologies other than mobile).

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[116] This is potentially an example of regulatory capture on the part of powerful mobile operators.

APPENDIX F - BROADBAND DEFINED

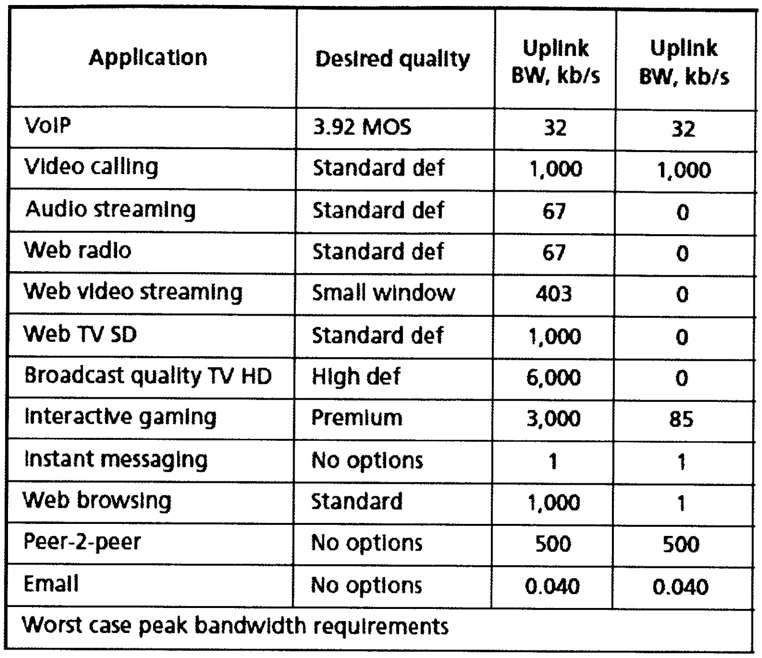
"Broadband" is widely used as a differentiating term in internet policy literature, including national and global statistics. For countries such as Kenya, where expanding "broadband" access is an area of active government intervention, the definition of what qualifies as broadband can have a profound effect on the approach to infrastructure expansion, including target areas and technologies.

While there is an absence of a technological consensus on how broadband is defined, its value proposition is clear. Broadband is valued for its transformative properties. It has the ability to change the way people work, communicate and access information. Such changes are often associated with positive social and economic effects (Lehr, Osorio & Gillett, 2005).

Anderson identifies three characteristics that make broadband transformative: Flat-rate billing, always-on connectivity and data transfer speed. These three characteristics combine to create an interface that encourages more frequent use and online exploration in what Anderson calls the "broadband virtuous loop" (Anderson et al. 2002).

While flat-rate billing and always-on connectivity are both self-explanatory and absolute, transfer speed is relative to the requirements of salient online applications. Bandwidth requirements for web-based applications have progressively grown as the internet has matured. Just as a modern PC must be hundreds of times more powerful than one from the 1980s to provide the same level of responsiveness with today's applications, the performance of broadband must grow with the requirements of modern internet use in order to maintain the transformative benefits we expect from broadband use.

Table 16 (Krogfoss et al. 2011) illustrates typical downstream bandwidth requirements for common online applications:



Application	Desired quality	Uplink BW, kb/s	Uplink BW, kb/s
VoIP	3.92 MOS	32	32
Video calling	Standard def	1,000	1,000
Audio streaming	Standard def	67	0
Web radio	Standard def	67	0
Web video streaming	Small window	403	0
Web TV SD	Standard def	1,000	0
Broadcast quality TV HD	High def	6,000	0
Interactive gaming	Premium	3,000	85
Instant messaging	No options	1	1
Web browsing	Standard	1,000	1
Peer-2-peer	No options	500	500
Email	No options	0.040	0.040
Worst case peak bandwidth requirements			

TABLE 16: APPROXIMATE BANDWIDTH REQUIREMENTS FOR ONLINE APPLICATIONS

The values above are only approximate, but it is clear that a connection capable of supporting an online experience that includes browsing, audio/video streaming and video chat requires downstream bandwidth is approaching a peak download speed of no less than 1Mbps, and an upstream bandwidth of at least 256Kbps. For real-time applications, we might also consider the importance of latency, and jitter. Jitter of greater than 200ms will disrupt most voice calls, while latencies of more than a few hundred milliseconds will degrade the experience of interactive applications such as remote computing.

APPENDIX G: FROM-CASH VS. CONTINUOUS GROWTH

Net Income 20

Highlighted cells on the following page show crossover ponits

Growth From Available Cash Only					
Months	Tot. Nodes	New Nodes	Cash, 1	Expense	Cash Bal.
0	1	1	400	400	0
1	1	0	20	0	20
2	1	0	20	0	40
3	1	0	20	0	60
4	1	0	20	0	80
5	1	0	20	0	100
6	1	0	20	0	120
7	1	0	20	0	140
8	1	0	20	0	160
9	1	0	20	0	180
10	1	0	20	0	200
11	1	0	20	0	220
12	1	0	20	0	240
13	1	0	20	0	260
14	1	0	20	0	280
15	1	0	20	0	300
16	1	0	20	0	320
17	1	0	20	0	340
18	1	0	20	0	360
19	1	0	20	0	380
20	1	0	20	0	400
21	2	1	40	400	40
22	2	0	40	0	80
23	2	0	40	0	120
24	2	0	40	0	160
25	2	0	40	0	200
26	2	0	40	0	240
27	2	0	40	0	280
28	2	0	40	0	320
29	2	0	40	0	360
30	2	0	40	0	400
31	3	1	60	400	60
32	3	0	60	0	120
33	3	0	60	0	180
34	3	0	60	0	240
35	3	0	60	0	300
36	3	0	60	0	360
37	3	0	60	0	420
38	4	1	80	400	100
39	4	0	80	0	180
40	4	0	80	0	260

Enforced Growth Rate of 2 Nodes/mo.				
Months	Tot. Nodes	Expense	Cash, 1	Debt Bal.
0		400	400	0
0.5	1	400	10	390
1	2	400	20	773
1.5	3	400	30	1149
2	4	400	40	1518
2.5	5	400	50	1879
3	6	400	60	2234
3.5	7	400	70	2581
4	8	400	80	2920
4.5	9	400	90	3253
5	10	400	100	3577
5.5	11	400	110	3895
6	12	400	120	4204
6.5	13	400	130	4506
7	14	400	140	4801
7.5	15	400	150	5087
8	16	400	160	5366
8.5	17	400	170	5637
9	18	400	180	5900
9.5	19	400	190	6155
10	20	400	200	6402
10.5	21	400	210	6641
11	22	400	220	6871
11.5	23	400	230	7094
12	24	400	240	7308
12.5	25	400	250	7514
13	26	400	260	7711
13.5	27	400	270	7900
14	28	400	280	8080
14.5	29	400	290	8252
15	30	400	300	8415
15.5	31	400	310	8569
16	32	400	320	8714
16.5	33	400	330	8850
17	34	400	340	8978
17.5	35	400	350	9096
18	36	400	360	9206
18.5	37	400	370	9306
19	38	400	380	9397
19.5	39	400	390	9479
20	40	400	400	9551

41	4	0	80	0	340
42	4	0	80	0	420
43	5	1	100	400	120
44	5	0	100	0	220
45	5	0	100	0	320
46	5	0	100	0	420
47	6	1	120	400	140
48	6	0	120	0	260
49	6	0	120	0	380
50	6	0	120	0	500
51	7	1	140	400	240
52	7	0	140	0	380
53	7	0	140	0	520
54	8	1	160	400	280
55	8	0	160	0	440
56	9	1	180	400	220
57	9	0	180	0	400
58	10	1	200	400	200
59	10	0	200	0	400
60	11	1	220	400	220
61	11	0	220	0	440
62	12	1	240	400	280
63	12	0	240	0	520
64	13	1	260	400	380
65	13	0	260	0	640
66	14	1	280	400	520
67	15	1	300	400	420
68	16	1	320	400	340
69	16	0	320	0	660
70	17	1	340	400	600
71	18	1	360	400	560
72	19	1	380	400	540
73	20	1	400	400	540
74	21	1	420	400	560
75	22	1	440	400	600
76	23	1	460	400	660
77	24	1	480	400	740
78	25	1	500	400	840
79	27	2	540	800	580
80	28	1	560	400	740
81	29	1	580	400	920
82	31	2	620	800	740
83	32	1	640	400	980
84	34	2	680	800	860
85	36	2	720	800	780
86	37	1	740	400	1120
87	**39**	**2**	**780**	**800**	**1100**
88	41	2	820	800	1120
89	43	2	860	800	1180
90	45	2	900	800	1280

20.5	41	400	410	9614
21	42	400	420	9667
21.5	43	400	430	9711
22	44	400	440	9745
22.5	45	400	450	9769
23	46	400	460	9784
23.5	**47**	**400**	**470**	**9788**
24	48	400	480	9783
24.5	49	400	490	9767
25	50	400	500	9742
25.5	51	400	510	9706
26	52	400	520	9660
26.5	53	400	530	9604
27	54	400	540	9537
27.5	55	400	550	9460
28	56	400	560	9372
28.5	57	400	570	9273
29	58	400	580	9164
29.5	59	400	590	9044
30	60	400	600	8913
30.5	61	400	610	8771
31	62	400	620	8618
31.5	63	400	630	8454
32	64	400	640	8278
32.5	65	400	650	8091
33	66	400	660	7893
33.5	67	400	670	7683
34	68	400	680	7462
34.5	69	400	690	7229
35	70	400	700	6984
35.5	71	400	710	6727
36	72	400	720	6458
36.5	73	400	730	6178
37	74	400	740	5885
37.5	75	400	750	5579
38	76	400	760	5262
38.5	77	400	770	4932
39	78	400	780	4590
39.5	79	400	790	4235
40	80	400	800	3867
40.5	81	400	810	3487
41	82	400	820	3093
41.5	83	400	830	2687
42	84	400	840	2267
42.5	85	400	850	1835
43	86	400	860	1389
43.5	87	400	870	929
44	88	400	880	456
44.5	89	400	890	-30
45	90	400	900	-530

APPENDIX H: LINKS, COVERAGE, SPECTRUM AND ROUTING

LINK-BUDGET AND WIRELESS COVERAGE

The most important calculation in the construction of a wireless link is the link budget. The calculation of link budget reveals whether or not a particular link is viable at the desired speed over the desired distance. In simplified form, a link budget is:

Allowed Loss (dB) = Transmitter Power (dBm) + Gains (dBi) – Receive Sensitivity (dBm) ***11.***

In Equation 11, the *Transmitted Power* is determined by the radio transmitter, *Gains* are determined by the antenna or RF reflector used and *losses* come from cables, attenuation from obstacles and free space loss of the signal as it travels between the sender and receiver. The *Receive Sensitivity* is determined by the device sensitivity at the desired bitrate, modified by the noise floor (as compared to the theoretical thermal noise floor) [117].

The value of the Received Power determines the maximum bitrate that can be transmitted. This is because more complex encoding schemes require a stronger Signal to Noise Ratio (SNR) to be decoded. For example, Table 1Table 17 shows the minimum receive signal strengths for different encodings[118] using the Ubiquiti NanoStationM5-Loco.

The sensitivities in Table 17 are applicable in the absence of ambient RF noise. In a real environment, RF noise from other transmitters may increase the received signal strength value needed to achieve a particular rate. For example, in our Njabini pilot, we were able to operate a very poor 2.4Ghz link (-80dBm) with goodput exceeding 10Mbps over a distance of more than 2km. In many urban environments (including our own Kendall Square) these two radios would often not even associate with each other due to a noise floor that can exceed -70dBm. In my experience, -95dBm is reasonable estimate of ambient noise for most Greenfield deploys, though I have measured noise floors as low as -100dBm[119] at sites in Afghanistan.

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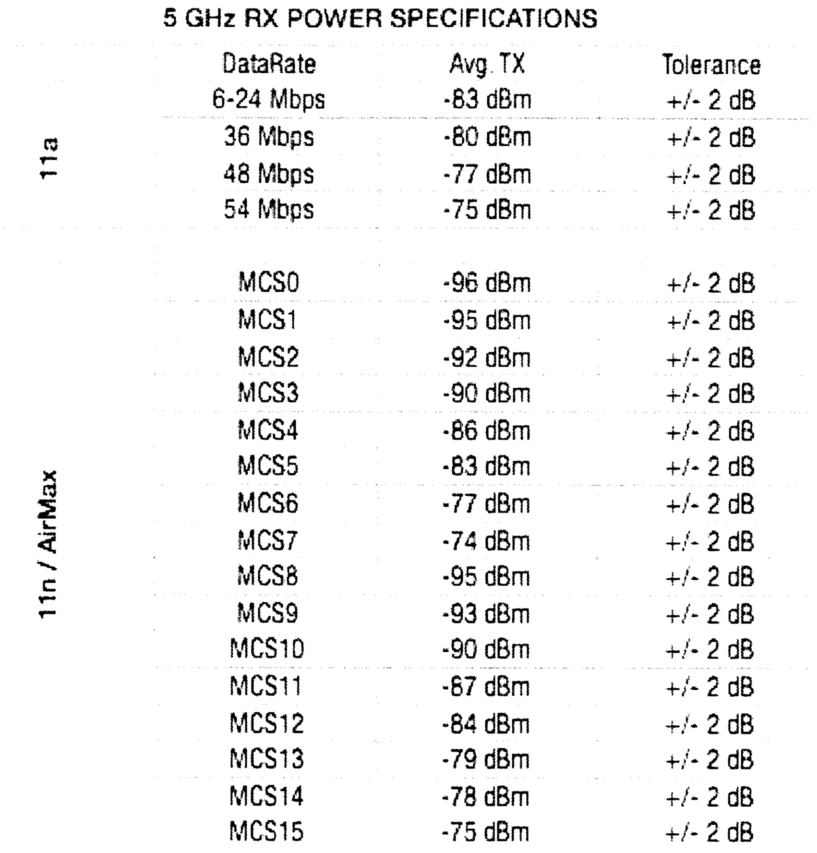
[117] The thermal noise floor for a 20Mhz channel at room temperature is approximately -101dBm, given by the approximation $P_{dBm} = -174 - 10\log_{10}(\Delta f)$ (Gilmore 2009).

[118] See http://linuxwireless.org/en/developers/Documentation/ieee80211/802.11n#MCS_Rates for more information on MCS Rates and encoding schemes.

[119] Using the Wi-Spy USB spectrum analyzer and Chanalyzer software http://www.metageek.net/products/wi-spy/



5 GHz RX POWER SPECIFICATIONS

	DataRate	Avg. TX	Tolerance
11a	6-24 Mbps	-83 dBm	+/- 2 dB
	36 Mbps	-80 dBm	+/- 2 dB
	48 Mbps	-77 dBm	+/- 2 dB
	54 Mbps	-75 dBm	+/- 2 dB
11n / AirMax	MCS0	-96 dBm	+/- 2 dB
	MCS1	-95 dBm	+/- 2 dB
	MCS2	-92 dBm	+/- 2 dB
	MCS3	-90 dBm	+/- 2 dB
	MCS4	-86 dBm	+/- 2 dB
	MCS5	-83 dBm	+/- 2 dB
	MCS6	-77 dBm	+/- 2 dB
	MCS7	-74 dBm	+/- 2 dB
	MCS8	-95 dBm	+/- 2 dB
	MCS9	-93 dBm	+/- 2 dB
	MCS10	-90 dBm	+/- 2 dB
	MCS11	-87 dBm	+/- 2 dB
	MCS12	-84 dBm	+/- 2 dB
	MCS13	-79 dBm	+/- 2 dB
	MCS14	-78 dBm	+/- 2 dB
	MCS15	-75 dBm	+/- 2 dB

TABLE 17: RX SENSITIVITIES FOR UBIQUITI NANOSTATIONM5-LOCO

Returning to the issue of the mesh network, a viable link must have losses smaller than the Allowed Losses from the link budget in Equation 11. Thus, the link budget determines the maximum limits for link lengths (in the backhaul network) and coverage (in the access network).

If we desire MCS15 on the NanoStationM5-Loco with a noise floor of -95dBm, we require a received signal of -75dBm plus the difference between the thermal noise floor and the real noise floor, making our target before fading: -75 + (101 - 95) = -69dBm. Given that our device has a transmit power of 17dBm[120] at MCS15 and an antenna gain of 13dBi with no cable losses[121], we have a link budget of 17 + 13*2 – (-69) = 112dB[122].

---

[120] 17dBm is a software limitation of the Ubiquiti firmware. By replacing the firmware with OpenWRT we are able to increase the transmit power above this value to potentially as high as 30dBm, but for conservative calculations we are using the factory firmware values in the calculation.

[121] The device uses an integrated antenna so there are no cable losses.

[122] Antenna gains from each end of the link are summed, which is why the gain of 13 is multiplied by 2.

Losses in the network come primarily from free space loss (as calculated in Equation 12 where d is the distance in kilometers and f is the frequency in megahertz), antenna cables/connectors (we have none in our system), and obstacles obstructing LOS[123]

We calculate the free-space loss according to Equation 12.

$$Loss_{dB} = 20\log_{10} d + 20\log_{10} f + 32.44 \tag{12.}$$

(V. Jones n.d.)

It is also common to add a "fade margin" to account for variations in weather conditions, such as very heavy rain, or link degradation due to misalignment of directional antennas over time[124,125]. We set this value at 5dB.

Continuing the analysis for the NanoStationM5-Loco, we calculate that over a 1km link, free-space loss is 107.8dB[126]. Adding a fade margin of 5dB, we have a total loss of 111.8dB, which satisfies the link budget of 112dB.

While long-range PtP links are relatively easy to make at the distances outlined in this paper[127], the issue of WiFi coverage to client devices is somewhat more complex. Unlike PtP links, access networks must communicate with multiple clients, using diverse hardware, over varying distances. Often times these links are not strictly LOS; and, almost invariably, the client devices operate with weaker radios and lower-gain antennas than the access devices. For an access network, it is the client device that poses the limitation on coverage.

Take for example the Lenovo laptop I am using to compose this document. It transmits at 14dBm with an omni-directional antenna that is likely 3dBi or less. Access nodes with

---

[123] LOS includes the Fresnel radius, which is the required clear radius surrounding the direct signal path, as calculated by $r = 17.31\sqrt{\frac{d_1 * d_2}{f * d}}$ where d_1 and d_2 are the distance from the point of interest to each end of the link, d is the total link distance and f is the frequency in megahertz. A general rule of thumb is that a link must have at least 60% Fresnel zone clearance along the entire signal path to avoid significant attenuation (Flickenger 2007, pp.23–24).

[124] This value is subjective, and rules of thumb vary widely. 20dB is a commonly quoted value for high reliability links when working directly with receiver sensitivities such as those shown in Table 17, but because we are accounting for the empirically determined noise floor and targeting the high (least negative dB value) range of the receiver's sensitivity, we choose 5dB as a margin value.

[125] http://www.afar.net/rf-link-budget-calculator/ provides an easy to use link budget calculator

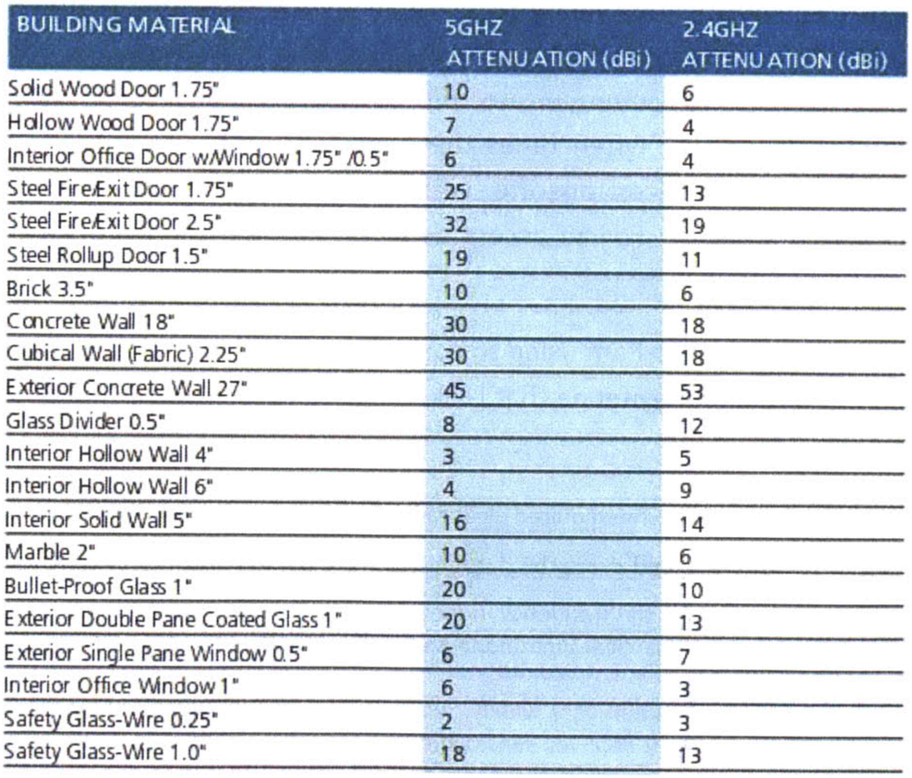
[126] Using a frequency of 5800Mhz

[127] In addition to the simplicity of LOS transmission to fixed points, PtP links are easily enhanced by inexpensive direction RF Reflectors or antennas. In Kenya, we made a 3.5km PtP wireless link using NanoStationsM5-Loco devices by using them as the feed element of a homemade parabolic dish (~40" across). This configuration provided 15dBi of additional gain on each end of the link.

24dBm transmit power and 6dBi antennas can reach me at MCS15 over a distance of nearly 700m[128] with 5dB of fade margin; however, in the reverse direction, I can only achieve MCS11 over the same distance, offering slightly less than half the speed of MCS15[129]. In general this situation is acceptable because upload requirements are generally much lower than for downloads, but it illustrates the point that client devices are a limitation.

The limitation of client devices can be mitigated to some degree by increasing antenna gain and decreasing transmitter gain on the access node (increasing one without decreasing the other would result in violating regulatory requirements), but this has the disadvantage of increased directivity, which could result in areas with poor coverage.

Obstacles further complicate the access network. If we add the requirement of penetrating a wall at a cost of 20dBm, the maximum coverage distance decreases to 70m. Table 18 illustrates the attenuation of wireless signals when passing through various building materials.



BUILDING MATERIAL	5GHZ ATTENUATION (dBi)	2.4GHZ ATTENUATION (dBi)
Solid Wood Door 1.75"	10	6
Hollow Wood Door 1.75"	7	4
Interior Office Door w/Window 1.75" /0.5"	6	4
Steel Fire/Exit Door 1.75"	25	13
Steel Fire/Exit Door 2.5"	32	19
Steel Rollup Door 1.5"	19	11
Brick 3.5"	10	6
Concrete Wall 18"	30	18
Cubical Wall (Fabric) 2.25"	30	18
Exterior Concrete Wall 27"	45	53
Glass Divider 0.5"	8	12
Interior Hollow Wall 4"	3	5
Interior Hollow Wall 6"	4	9
Interior Solid Wall 5"	16	14
Marble 2"	10	6
Bullet-Proof Glass 1"	20	10
Exterior Double Pane Coated Glass 1"	20	13
Exterior Single Pane Window 0.5"	6	7
Interior Office Window 1"	6	3
Safety Glass-Wire 0.25"	2	3
Safety Glass-Wire 1.0"	18	13

TABLE 18: WIFI ATTENUATION THROUGH VARIOUS MATERIALS

(3Com n.d.)

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[128] Using the same values for receive sensitivity as the NanoStationM5-Loco

[129] Note, these bitrates are theoretical maximums.

Table 19 illustrates the maximum distances that each of the components of the network could theoretically transmit at their highest encoding[130], given a 5dB fade margin:

	Distance at:		
Device	Maximum Bitrate	90% Maximum Bitrate	Notes
NanoBridgeM5 22	8.2km	12.9km	
NanoBridgeM5 25	16.3km	25.8km	
NanoStationM5-Loco	0.9km	1.5km	
PicoStationM2-HP	70m	100m	Includes 20dB of attenuation for obstacles. Assumes upload speeds are lower than download and that receive sensitivities for laptop are similar to that of the PicoStation.

TABLE 19: MAXIMUM TRANSMIT DISTANCE FOR WIRELESS DEVICES WITH 5DB FADE MARGIN

COVERAGE MODEL

By nature, an omni-directional antenna creates a circular coverage area around the access point. When modeling wireless coverage, our analysis takes the conservative approach of modeling wireless coverage using a hexagonal area inset into the coverage circle, as shown in Figure 15.

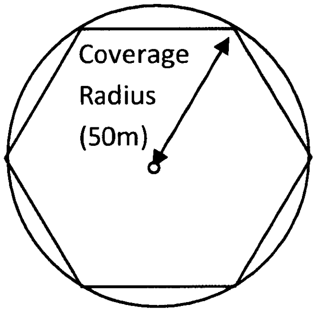

FIGURE 15: COVERAGE MODEL FOR ACCESS NODE

To additionally ensure that we do not overestimate useful coverage, we use a coverage radius of 50m, as opposed to the theoretical 70m obtained from the link budget calculation.

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[130] Maximum encoding is MCS15 or MCS7, depending on whether the device can transmit one or two spatial streams. The NanoStationM5-Loco and NanoBridgeM5 devices are capable of MCS15. PicoStation M2-HP is capable of MCS7.

MESH VS. CELLULAR BASE STATION

A critical advantage of the mesh approach, particularly in the case of difficult geography, is the ability to build networks around obstacles (Methley 2009, pp.24–35) and test coverage empirically. This is much more difficult and expensive to do with a single base station having a coverage radius of many kilometers. The mesh model also avoids the need for long-distance tower-ground links by using PtP links to cover long distances; thus, decreasing the radius of the access layer. The PtP + local access approach avoids much of the destructive multi-path interference that long-distance access layer links are susceptible to (Wilton & Charity 2008, pp.79–81). These features make mesh deployment more accessible to SSOs.

MESH ROUTING AND NETWORK DESIGN

In any networking infrastructure, fault tolerance is an important consideration. In enterprise networks, fault tolerance is generally a statically engineered and manually configured feature, usually making use of redundant hardware and pre-conceived failover states. While this fault tolerance may accomplished in a distributed fashion, such as with BGP routing between autonomous systems in the internet core, it is pre-configured with much thought and planning by networking experts.

The CWN model necessarily takes a very different approach to fault tolerance. Instead of monolithic, failure-proofed facilities, the CWM depends on the existence of many less-reliable devices' dynamic cooperation (through mesh networking) to minimize single points of failure on the network. In a wireless mesh, each device maintains sufficient routing information to determine, at any given time, all the paths to reach any other node in the network[131]. As a result, mesh networks are able to quickly reroute traffic around individual node failures. For readers who are Sci-fi Fans, an apt analogy for a mesh network is The Borg from Gene Rodenberry's *Star Trek: Next Generation*. In the Borg society, each individual is connected to a collective intelligence that allows all members to share information about the state of the collective. Killing any one member of the collective has little effect on the whole because the other members instantly recognize the loss and compensate for the lost function. Similarly, in a well-configured mesh, a single node failure only affects the users directly connected to the failed node, leaving the rest of the network operational. In denser meshes, the re-use of access radios (or addition of a secondary 2.4Ghz radio, as pictured in Figure 16) in a pure ad

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[131] Modern mesh protocols such as B.A.T.M.A.N (http://www.open-mesh.org/) and OLSR-NG (http://www.olsr.org/) implement optimizations to brute-force collection and calculation of routing information for the entire network on each node that allow scaling into the thousands of nodes.

hoc mesh configuration as a backup means of moving traffic can make the mesh highly resistant to total failures. Figure 16 shows an example of this type of mesh. In the figure, solid lines are 5Ghz links (colors indicate different channels). Hexagons indicate access network coverage. Halos around each hexagon indicate the 2.4Ghz ad hoc mesh channel, while hexagon color indicates access channel.

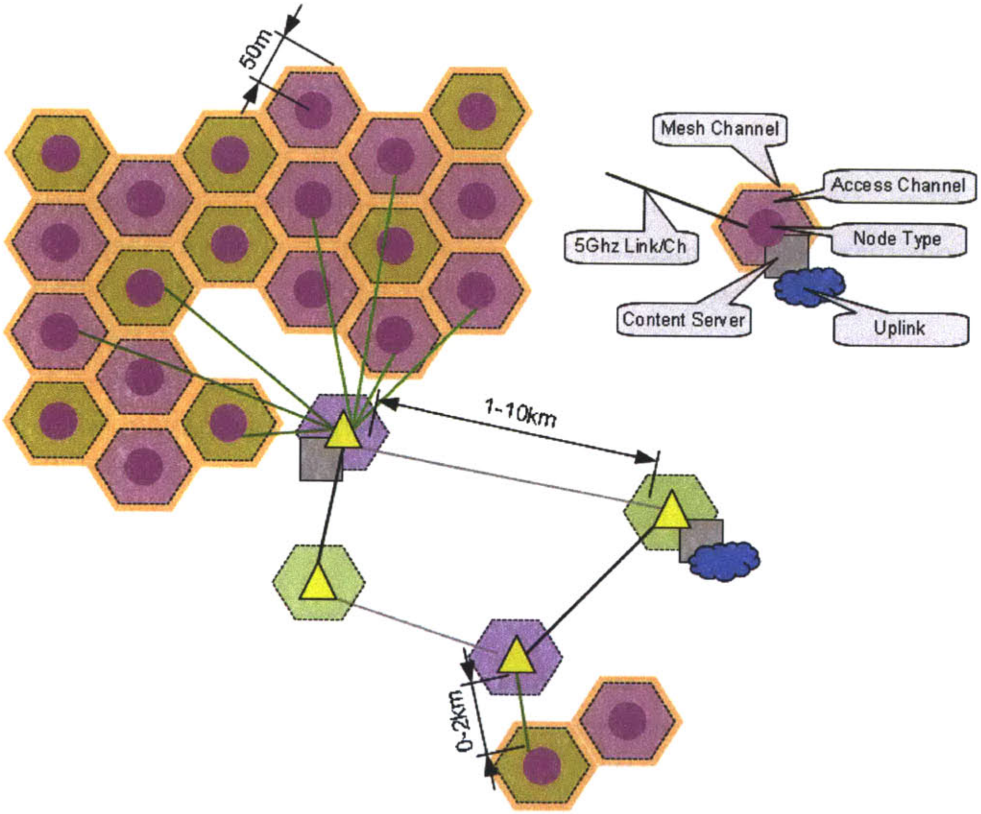


FIGURE 16: INFRASTRUCTURE MESH WITH 5GHZ INFRASTRUCTURE MESH AND 2.4GHZ AD HOC MESH CONNECTIVITY

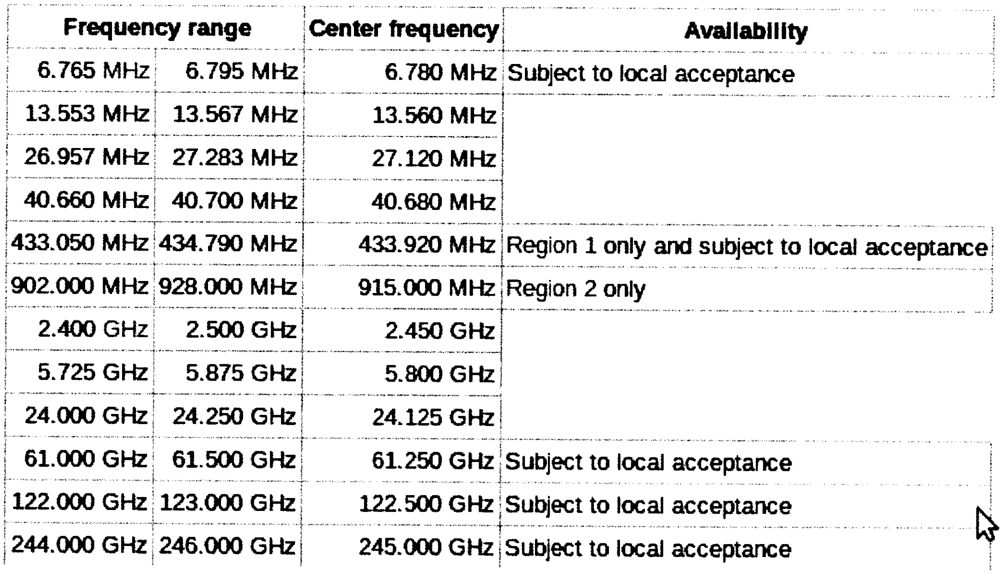
Another important feature of mesh architecture is the ability to build networks without prior knowledge of the network topology (because the routing protocols automatically manage routing). This simplifies the process of expanding networks in an ad hoc manner in response to demand.

In the case of the SSO, however, mesh networking does not entirely resolve the problem of network design in every situation. In order to maintain network performance, an operator must carefully choose wireless channels to decrease interference between adjacent links. When using directional antennas on the network backbone, the operator must also ensure that redundant paths through the network exist in case of node failures.

At the scale of the networks described in this paper, such design can be undertaken manually by a well-trained operator, but automated tools for performing channel optimizations and identifying single points of failure within the network could improve performance at much larger scales. Some work has been undertaken in this domain, such as that of Marina et al. (2009), but easy-to-use in-network tools have yet to become readily available.

SPECTRUM REGULATIONS AND WIRELESS CAPACITY

As mentioned in 4.3.1, the absence of spectrum licensing is a necessary feature for the success of the CWN model. As a result, the amount of available unlicensed spectrum and the regulations regarding this spectrum have significant bearing on whether CWNs are viable in a particular country. Countries conforming to ITU regulations reserve multiple spectrum blocks for "Industrial Scientific and Medical". These bands, as described in Table 20, are generally open to use by unlicensed operators; however, this does not always mean such use is unregistered or free of charge. For example, Michael Best's 2006 analysis of an ITU global survey on WLAN regulations revealed that respondents were evenly divided between unlicensed, registered and licensed use of WLAN frequencies in the 2.4Ghz and 5Ghz bands (2006).



Frequency range		Center frequency	Availability
6.765 MHz	6.795 MHz	6.780 MHz	Subject to local acceptance
13.553 MHz	13.567 MHz	13.560 MHz	
26.957 MHz	27.283 MHz	27.120 MHz	
40.660 MHz	40.700 MHz	40.680 MHz	
433.050 MHz	434.790 MHz	433.920 MHz	Region 1 only and subject to local acceptance
902.000 MHz	928.000 MHz	915.000 MHz	Region 2 only
2.400 GHz	2.500 GHz	2.450 GHz	
5.725 GHz	5.875 GHz	5.800 GHz	
24.000 GHz	24.250 GHz	24.125 GHz	
61.000 GHz	61.500 GHz	61.250 GHz	Subject to local acceptance
122.000 GHz	123.000 GHz	122.500 GHz	Subject to local acceptance
244.000 GHz	246.000 GHz	245.000 GHz	Subject to local acceptance

TABLE 20: ITU ALLOCATIONS OF ISM FREQUENCIES

(International Telecommunication Union 2007)[132]

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[132] Table Reprinted from http://en.wikipedia.org/wiki/ISM_band#ISM_bands

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