Technology Insights for Rural Connectivity

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September 2005

We believe that wireless infrastructure can have an unprecedented positive impact on the economic and social development of the rural areas of developing regions. We look at four aspects of rural connectivity that are poorly understood and that should affect both proposed solutions and policy: the limitations of cellular, the need to focus on non-mobile endpoints, the use of unlicensed spectrum, and wireless links as an alternative for fiber. Finally, we review some of the leading technologies for rural connectivity.

Introduction

The story of economic development is in large part a story about infrastructure. Water supply, transportation networks, and communication systems worldwide are all anthologies about innovative infrastructure driving economic efficiency and playing a vital support role in social development, education and the overall quality of life.

Rural life in the least developed countries (LDCs) can be defined in part by the absence of much infrastructure. Transportation, electricity, water, and communication infrastructures (among others) are generally quite limited; in fact the World Bank's *Human Development Index* is indirectly a measure of infrastructure deployment and correlates quite well other more direct measures such as the *Networked Readiness Index* (NRI) [GITR]. There many other problems beside infrastructure even within the "digital divide" — content, policy, cultural factors among them — but here we will focus primarily on the infrastructure.

And the absence of infrastructure in rural areas follows directly from the low population density: the cost of infrastructure is generally proportional to the area covered, while the benefit depends on the number of people affected. Thus, unlike urban areas, the cost of infrastructure on a per person basis is simply too high: even if capital is readily available and government hurdles are low, the net increase in productivity due to the infrastructure is limited by the density, and thus cannot sustain the investment based on return alone.

The Wireless Hypothesis

The most impressive infrastructure rollout in LDCs by far as been the deployment of cellular telephony. In addition to broad usage in China, India and other Asian countries, Africa has become the fastest growing cellular market. But even this revolution has been primarily an urban phenomenon, as we discuss in more detail below.

But despite these limitations, the forces that enabled urban cellular infrastructure are still at work: the movement of wireless protocols into integrated circuits means that we can expect tremendous progress in wireless capabilities for the foreseeable future. Thus, we hypothesize two impacts:

1. **Wireless technology will be the first viable infrastructure** (of any kind) for rural areas. Existing roads are potentially the exception to this, and there is also an argument for some water systems, such as aqueducts or the rice paddies in Bali. The costs for wireless will be so low that wireless infrastructure will be viable for the majority of world's population.

2. **Economic growth from connectivity can lead to the viability and thus arrival of other infrastructures**. This point is mostly optimism at this point, but represents the essence of why we work in this area.

We make no attempt to prove these points in this paper, but rather treat them as motivation. Instead, we focus on four of the fine points in wireless technology that are rarely well understood. These four are that: 1) cellular alone will not be enough, 2) connectivity is more viable without mobility, 3) unlicensed spectrum is the right short-term path, and 4) wireless should replace fiber for large-scale Internet projects. We then look at three of the most viable wireless technologies, and conclude.

Point 1: Cellular Telephony is Not Enough

Rural cellular telephony coverage is a good example of the low cost/benefit ratio for rural infrastructure in action. Grameen Telecom in Bangladesh is a great rural cellular success story, however its success depends on two factors that make it hard, though not impossible, to replicate. First, Bangladesh has a very high population density, which obviously increases the return on investment. Second, although there are many rural phones, there are almost no "rural" basestations: the basestations are subsidized by urban users, including those travelling along major transportation routes (road and rail). And in fact the villages that do not have coverage (about 15,000 out of 68,000) are exactly those that are out of range of a subsidized basestation, and the cost of deploying a basestation in range does not make economic sense due to the low density.

Similarly, Reliance LTD in India has announced an ambitious plan to cover 80% of India with their network, but this plan also depends on the use of basestations along transportation routes for their primary customer base [TG05]. Countries with lower population density (such as most of those in Africa) or those with a very small "primary" customer group (most LDCs), will be unable to implement this model based solely on return on investment.

The other general approach is to decree the deployment of infrastructure as a national goal even though it may not make (short-term) economic sense. This is certainly the strategy of China, which has good cellular coverage even in some very remote places. This was also the strategy for ancient aqueduct systems and most rail and airline systems. A related strategy is the use of subsidies or the creation of local monopolies, such as the cable infrastructure in the US, in which the goal of the policy is to try to increase investment returns to the point of viability.

Thus, overall, there is a myth that cellular technology will simply solve the connectivity problem, when the reality is that it will solve it only where density is sufficient and legal and policy risks are low. The rural areas of LDCs rarely fit these criteria.

Point 2: Make room for Connectivity without Mobility

A side effect of the focus on cellular telephony is some degree of confusion between wireless networking and cellular wireless for mobile users. **Rural connectivity is significantly more likely to be viable if we focus on non-mobile endpoints.** Part of achieving this focus is education for both policy makers and investors on the cost of mobility, and on the need to distinguish between solutions for mobile handsets and solutions for rural connectivity, which can easily co-exist with the right policies.

The first problem with mobility is that it implies an unnecessarily large coverage area: all the places that mobile users are likely to be. In practice, connectivity just to schools and key public spaces (such as markets or temples), covers a tiny fraction of a rural area, and is thus significantly cheaper to deploy. The downside of targeted connectivity is that it is harder to use and therefore less impactful than full coverage, but given the cost difference, which is more than an order of magnitude, it seems better to start with limited coverage and expand it as the economy grows. This mirrors the strategy in practice of most cellular carriers: they deploy first to high-density affluent areas and use that revenue to spread out from there.

The *mechanism* of targeted coverage is the use of directional antennas. A typical "24 dBi" antenna, which costs about US$80 in India, enables a 5-degree beam that is amplified (using no power) by a factor of about 250. This enables hot spots of coverage with megabits of bandwidth that are more than 30km from the tower. These kinds of antennas are orthogonal to the particular wireless technology, and have even been used in Bangladesh for non-mobile village phones. An enterprising "phone lady" put up her own directional antenna to get a better signal, at the expense of the mobility of her handset.

A related advantage of stationary endpoints is that we can use lower transmission frequencies, such as 450MHz for CDMA450 (covered below), or 700 MHz, which has been proposed for use in India. These frequencies, often used for television, degrade less with distance, which makes them fundamentally cheaper for low-density areas as you can get fewer cells or more bandwidth for a given distance. However, in mobile settings the advantages of having a better signal are hindered by the large size of the antennas required, which makes the handsets bulky and awkward. Moreover, receiver diversity (receiving simultaneously on two antennas and combining the signal), a technique that accounts for up to 70% improvement in achieved bandwidth, is very difficult to utilize in mobile handsets, due to the large size implied by two antennas in different directions. Thus a good general policy is to use lower frequencies for rural connectivity and higher frequencies for mobility.[1]

1. One big exception is the use of more complex "smart" antennas, which can negate the distance advantage of lower frequencies. In the short term these antennas are too expensive, but they are also impacted by integration into chips and will be viable relatively soon. We are building a low-cost smart antenna for the 5.8GHz range and will see how it progresses.

Stationary endpoints also enable multi-hop or mesh networks, which combine very well with targeted coverage. In multi-hop rural networks, packets are sent from village to village until they reach a village with wired connectivity. Multi-hopping is very difficult (albeit not impossible) with mobile endpoints, as it is very difficult to know the best path to connectivity, so mobile handsets always use one hop to the basestation. Thus, when connecting a village to a rural network, it is roughly sufficient to connect it to any village that already has connectivity (or to a basestation); this flexibility reduces costs and also makes good use of the spectrum. We have already demonstrated multi-hop village networks using WiFi (as have others) [RC05].

Yet another very important disadvantage of mobility relates to the maximum transmission power in handsets, which is limited by the scarce battery budget. In cellular networks, the range is limited by the low transmit power of the handsets, which is orders of magnitude smaller than the transmit power of the basestation (0.2W vs. 23W). Fixed installations can afford higher transmit power, and can consequently have longer ranges and higher bandwidth.

As a side note, with the cost of wireless circuits being driven down by Moore's Law, the dominant costs become those of the tower, the power, and the maintenance.[2] All three will benefit from more research. A normal cellular tower can range from US$2000-7000 depending on height, which is roughly 10x more than the cost of the electronics and antennas. In practice, the best bet seems to be using short poles on hills or existing tall buildings, rather than towers; however, this requires careful planning in terms of the locations. For example, in a telemedicine project in southern India, we are choosing the location of a rural health center based in part of its visibility from likely pole locations. Similarly, a proposal for a national wireless network in Rwanda [cite] will benefit from its colloquial nickname: *Pays des Mille Collines* ("land of a thousand hills").

Point 3: Unlicense Now, License Later

Spectrum allocation is always a controversial topic, as it is hard to optimize the use of any limited public resource. However, in the case of rural connectivity there are some issues that tend not to be well understood.

First, it worth pointing out that since we are worried about the viability of rural connectivity, it makes no sense to auction off the spectrum — there are unlikely to be any buyers if it is really for rural use only. In most cases, the allocation includes both rural and urban users, and therefore it becomes an auction for the right to serve the *urban* users, but the winner also receives the spectrum rights in rural areas, which then go unused. Better awareness of this issue could lead to different rights or perhaps an obligation to offer service in a area or lose the right in that area. Alternatively, a government could *require* rural coverage from the winner as part of the auction rules; this lowers the value of the license and also implies a subsidy from urban to rural users.

Because the rural solution remains unclear, at least some spectrum should be allocated for unlicensed use, as is now occurring in several countries in the WiFi spectrum (2.4GHz). Unlicensed use has several important advantages, but the most important by far is that it enables researchers

2. These three dominate the cost for rural connectivity; for urban connectivity the costs are driven by network capacity (not coverage), and the electronics and amplifiers play a much bigger role.

and entrepreneurs to search for the right solution.

WiFi is easily the best choice for unlicensed spectrum allocation. Wifi components expect to be used in this fashion and are thus good at limiting the impact of interference. The components also typically have a short range, which makes it easy to have independent use just based on location. Finally, the very high volume of WiFi cards, more than 70M units in 2005, has led to very low-cost components, which also facilitates experimentation.

Unfortunately, unlicensed spectrum is only a short-term option for rural connectivity. The exact properties that you want for unlicensed systems, interference detection and short range, are not the right choices for a long-term rural connectivity solution. The short range is obviously wrong, but if you just increase the power and thus the range, you interfere over a wide area and defeat the purpose of unlicensed spectrum.

More subtly, the mechanism for avoiding interference is *listening*: if a node cannot hear another node, then it will transmit. This assumes that you can hear everyone with whom you could interfere, which is roughly true if you have short omnidirectional range.[3] However, given that we want long distances and targeted coverage, this is completely unrealistic.

Once a rural solution is proven, it will quickly be hindered by its use of unlicensed spectrum. It will not be possible to deliver a large-scale highly reliable service in unlicensed spectrum. Competitors will be unable to depend on bandwidth and could even sabotage each other legally. Control of the spectrum is fundamental to the quality of the service.

Thus, we expect that unlicensed spectrum is the right first step, especially for experimentation with rural solutions. However, when a solution emerges it should be moved to its own spectrum that is licensed and possibly even auctioned off (since its value is now known). One possible policy would thus be to commit future spectrum as the reward for meeting specific rural connectivity milestones: this is analogous to the X Prize, but the reward is not cash but rather spectrum. As one example, in the Indian state of Kerala, the state government led the deployment effort directly as part of the Akshaya project [NP+05], using its control of the spectrum as part of the plan. This included a call for proposals and required demonstrations of rural wireless solutions, and has led to the largest rural wireless deployment to date, with roughly 400 connected rural kiosks.

Point 4: Explore Wireless instead of Fiber

The favorite solution to connectivity for most countries and big institutions such as the World Bank is the deployment of fiber. The advantage of fiber is clearly its nearly unlimited bandwidth. Given enough bandwidth demand, it will always be the right solution. But conversely, when bandwidth demand is low or not yet established, it is unlikely to be the right choice. The basic cost of fiber in India is about US$1000/km, which should be viewed as a lower bound for the cost anywhere else.

3. It also assumes that there is little or no delay between when they start transmitting and when you hear them, which is true for short ranges, but not for long ranges; the speed of light in air is roughly 10 microseconds per mile, so this effect matters in practice.

One example that has not gone well is the SAT-3 undersea fiber that goes around Africa from Portugal all the way to India and Malaysia (14,000 km). This fiber ring cost roughly US$650 million and has very little usage, and in fact has not led to low bandwidth costs in the associated countries. Part of the ineffectiveness stems from the "cartel" of monopoly phone companies that operate the fiber; it is not an efficient market. A typical quote from NiTel (Nigeria) is US$8,000 per megabit per month, which is extremely high and in fact is closest in pricing to satellite connectivity, which is often the only substitute (and fundamentally expensive). High prices also protect traditional international telephone revenue (and corresponding taxes), which would greatly decline in the presence of VoIP telephony, and have already declined just competing with e-mail.[4] Additionally, SAT-3 connections go only to Portugal, which means there are additional costs to get effective bandwidth to major data centers (such as London).[5]

Another part of the problem is that local operators are not well equipped to deliver the bandwidth to the marketplace once connected. To aggregate enough demand to justify a fiber requires a significant routing and switching infrastructure that simply doesn't exist, and significant resources and expertise for billing and network management as well. In practice, only a few large users (e.g. Shell Oil) with their own network resources can make the current model work.

The basic proposal here is to ignore fiber for now and build out backbones using long-distance wireless links. On the surface, this seems like a bad idea as the link bandwidth will not be very high and will pale in comparison to SAT-3, which is 120 gigabits per second (shared). But the basic argument is this: **build out the wireless backbone first, and when you run out of bandwidth you can upgrades links one at a time to fiber, on demand**. Since the network is essentially a tree in shape (rooted at a fiber point), this allows the network to expand very naturally based on local demand, with little up front capital and pay-as-you-go self-funding growth.

We expect that a 50km link will cost less than US$5000 counting power and poles. (The actual link is probably only US$500.) This comes out to US$100 per kilometer, or about 1/10 the best price for fiber (and better than that when you count the cost of the fiber equipment at each end). As for bandwidth, we will likely see less than 10 Mb/s in the short term, going up to 50 Mb/s given near-term technology, and long-term plans that might exceed 500 Mb/s (e.g. 802.11N). Although lower than fiber these bandwidths are sufficient to provide basic connectivity to a very large population. More importantly, when a link becomes full, it is not only easy to move to fiber, but you have the traffic to justify it and likely the revenue to pay for it.

This approach is also appealing because it could largely be done at the grass roots or NGO level given some unlicensed spectrum. Toward this end, we are trying to demonstrate a WiFi backbone from Accra to Kumasi in Ghana (about 200km) this winter. In addition to the technical hurdles,

4. Based on conversations with one African president, it is unlikely that governments will have the courage to open up fiber access. A very significant fraction of government revenue comes from telephone taxes or ownership of the monopoly phone company, so any real solution will need to replace that revenue. Ironically, revenue would likely go up if usage met projected demand, but the transition would be challenging.
5. Allowing low-cost international traffic within Africa might fix this, as there would at least be competition among the PTTs, but this is not likely in the near future, which is one reason they are referred to as a cartel. The IMF or WB could insist on this kind of structural change as part of future funding.

there is no unlicensed spectrum in Ghana, so we are partnering with someone that has a license for WiFi. Longer term, we cannot legally use the technology across national borders, so by itself this will not help bring down African international access prices, although the use of web caching would improve at least web access. (Technically, it would be relatively easy to connect the capitals of Ghana, Togo and Nigeria, for example.) We hope a successful demonstration will change the debate significantly.

A Quick Tour of Wireless Options

We next review at a high-level some of the most promising wireless technologies for rural connectivity. We are pursuing experiments with all three and believe that it is critical to push on multiple fronts — ideally leading to multiple viable solutions (and competition).[6]

The most promising evolution of cellular technology is CDMA450. CDMA is the technology developed by Qualcomm that is widely deployed as CDMA2000 for cellular networks not only in developed economies, but also in China, India and several LDCs. CDMA450 is a variation that runs at 450MHz, thus using a lower longer-distance frequency as discussed above. Although in use in a few places, the most interesting deployment to date is Zapp Networks in Romania, which is primarily an urban network so far. Using their network we were able to confirm connectivity for non-mobile endpoints at a distance of 50km with data connectivity of 1.3 Mb/s (the uplink was 110 kb/s). This looks to be a good solution for mixed data/voice service and also for large flat areas in which a single expensive tower could cover a large rural area.

Second, we believe the use of long-distance WiFi links is an important direction for rural wireless. The volume of WiFi components ensures low cost, but there are technical hurdles to overcome that are the subject of active research. In particular, the normal usage of WiFi (as defined by the 802.11 standards), provides short-range connectivity intended for sharing and with relatively poor support for voice connectivity. Instead, we need long-range point-to-point (non-shared) connectivity with good support for voice and video. Towards this end, we and others have developed new software that uses the same low-cost hardware and delivers on the desired properties. So far, we can demonstrate high-quality video and voice over a single 30km hop (about 5.5 Mb/s), and are working on multi-hop solutions and longer range. Assuming the mesh networking works, this will be a good solution for hilly areas or places with line of sight among villages (to minimize tower costs).

Finally, longer term we expect the new “WiMax” standard (802.16) to form a good solution. It is closer in spirit to CDMA450 than WiFi, in that it would use a single expensive basestation on a large tower. It will also have higher bandwidth and would be very suitable for replacing fiber for wireless backbone networks. However, there are some short- and long-term challenges. On the short-term side, the standards are still in flux and demonstration networks are still rare. In addition, although touted as a solution for developing countries, most of the current effort appears to be on high-bandwidth to mobile urban users, which is a much larger market. These are of course the wrong design goals for a rural solution, which reduces the chance the coming WiMax equip-

6. See the “Technology Primer” in [W2I] for more details on these options.

ment will form the basis of a rural solution; for example, it appears that basestations will be very expensive, very high power, and very high capacity, rather than being low on each metric. Support for mobility will also increase the cost. Longer term, the primary question is whether volume will be high enough to lead to the same low-cost components enjoyed by WiFi and cellular. Without this volume, WiMax will not be a viable solution. Nonetheless, we expect to perform WiMax trials with expensive equipment with the hope that the cost becomes viable over time.

Summary

We believe that rural connectivity has a chance to be a powerful new rural infrastructure that enables local economies and leads to education, social development, and in turn to other kinds of infrastructure. In the best case, rural connectivity will bring new options to these regions, produce a visible improvement in the quality of life, and reduce the pressure towards urbanization (with its associated societal costs). In addition to reviewing some of the candidate technologies, we covered four of the finer points of wireless connectivity that need to be more widely understood to make this vision happen.

Acknowledgements: Thanks to Sergiu Nedevschi, Joyojeet Pal, Rabin Patra and Sonech Surana for their help and comments.

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