Using Wireless Technology to Provide Basic Telephone Service in the Developing World

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Low-tier wireless systems offer great promise for the provision of basic telephone service in the developing world. Such systems offer the advantages of rapid deployment, minimal disruption during construction, and low cost. This paper examines the level of investment required to deploy such systems, exploring the question in the context of a number of design constraints and parameters. The analysis shows that the investment required to build a low-tier wireless system compares quite favorably with that of a conventional cable-based system. The paper concludes with some policy implications of the work that are relevant to national governments and telephone carriers in the developing world. Copyright © 1996 Elsevier Science Ltd

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The introduction of wireless personal communications services (PCS) may have created a new opportunity for areas of the developing world that currently have inadequate telephone service. Some manufacturers plan to produce equipment for the US market to provide 'low-tier' PCS services using the new 1.9 GHz PCS spectrum created by the Federal Communications Commission.[1] The equipment will use low transmitter power (up to 800 mW) and low base station antenna heights (5–20 m) to serve microcells (100–500 m radius). This approach will allow the provision of low cost wireless service to high concentrations of subscribers. Further, high bit rate (eg 32 kbps) voice coding techniques will allow high quality speech. According to its proponents, the low-tier service will be less complex and, therefore, less expensive than 'high-tier' PCS (conventional cellular) service. They say that it will be able to provide higher quality, lower cost service to higher subscriber densities than will high-tier service.[2]

Such low-tier wireless equipment may also hold promise for developing nations that currently have inadequate basic telephone service. For such nations, wireless offers the advantages of rapid deployment and less heavy construction, with its resultant disruption, than is required for the installation of cable plant. High-tier and low-tier systems share these advantages, but high-tier often requires greater investment than cable-based systems. Low-tier systems, on the other hand, offer the promise of smaller investment than high-tier systems and possibly smaller investment than cable-based systems. If this promise is fulfilled, low-tier systems will be a very attractive option for delivering basic telephone service in the developing world, providing the advantages of rapid deployment, less disruptive construction and low cost.

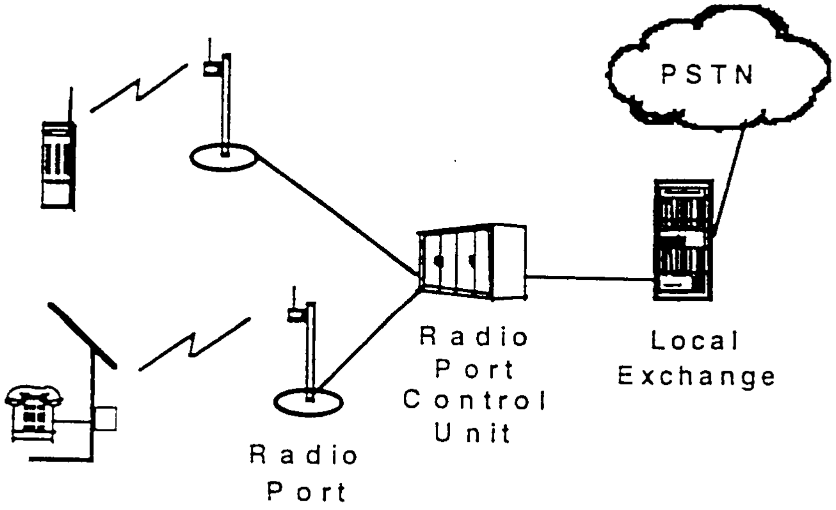

Figure 1. Structure of a low-tier wireless system.

In order to explore the costs of implementing low-tier wireless systems, we have built a computer-based model whose purpose is to estimate the required investment for such systems in cities of the developing world. Using this model, we have compared the required investment with that of building cable-based telephone systems in these cities.[3]

Manufacturers may soon begin to produce low-tier equipment for use in the United States. Some 1.9 GHz licensees are currently planning to deploy high-tier systems in the new spectrum, but others are considering low-tier equipment. If a compelling case can be made for the use of low-tier equipment in the developing world, this application alone may justify large-scale production by equipment manufacturers.

In a low-tier system, small handheld sets, or fixed wireless sets, referred to here as customer premises equipment (CPE), communicate with base stations called radio ports (RPs). An RP is a small unit, perhaps the size of an electric toaster, which can be mounted on a utility pole. The RPs are closely spaced, hundreds of meters apart. Such spacing, in combination with low transmit power, gives rise to the cells' small size.

As shown in Figure 1, a number of RPs are controlled by a single radio port control unit (RPCU). The RPCU, collocated with the local exchange, handles communication to the local exchange, hand-off between RPs it serves, and, possibly, hand-off between one of its RPs and an RP controlled by another RPCU. Here we assume that a single RPCU can control up to 24 RPs. The RPCUs are likely to have sufficient intelligence to handle the functions performed by the mobile telephone switching office (MTSO) in a cellular system, eliminating the need for a MTSO.

A low-tier system would be deployed in a city by siting the RPs according to some regular pattern. The distance between RPs must be small enough to insure that there are no coverage gaps, but large enough to allow an economical deployment. In our model, for simplicity, we assume that a city is composed of rectangular blocks with streets that run north–south and east–west. The RPs are placed on intersections every *n* blocks, where *n* is determined by the maximum cell radius and the distance between intersections. This layout produces square cells whose radius is defined as shown in Figure 2.

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developed using DEMOS software, a product of Lumina Decision Systems, Inc.

[1] The key order in allocating the 1.9 GHz spectrum to PCS was: Federal Communications Commission 'Second Report and Order' Docket 90-314 1994. The standard for low-tier PCS in the United States is PACS, which stands for Personal Access Communications Systems.

[2] A description of low-tier wireless systems is included in Cox, D 'Wireless personal communications: what is it?' *IEEE Personal Communications* 1995 2 (2) 20–35. A description of the advantages of microcellular (low-tier) systems can be found in Lee, W 'Smaller cells for greater performance' *IEEE Communications* 1991 29 (11) 19–23. The issues involved in designing such systems are described in Samecki, J, Vinodrai, C, Javed, A, O'Kelly, P and Dick, K 'Microcell design principles' *IEEE Communications* 1993 31 (4) 77–82. An overview of wireless systems generally is contained in Kucar, A 'Mobile radio: an overview' *IEEE Communications* 1991 29 (11) 72–85

[3] Others have investigated the economics of wireless service. See, for example, Reed, D 'The cost structure of personal communications services' *IEEE Communications* 1993 31 (4) 102–108. There is, to our knowledge, no previous published examination of the economics of using low tier wireless to provide basic telephone service in the developing world.

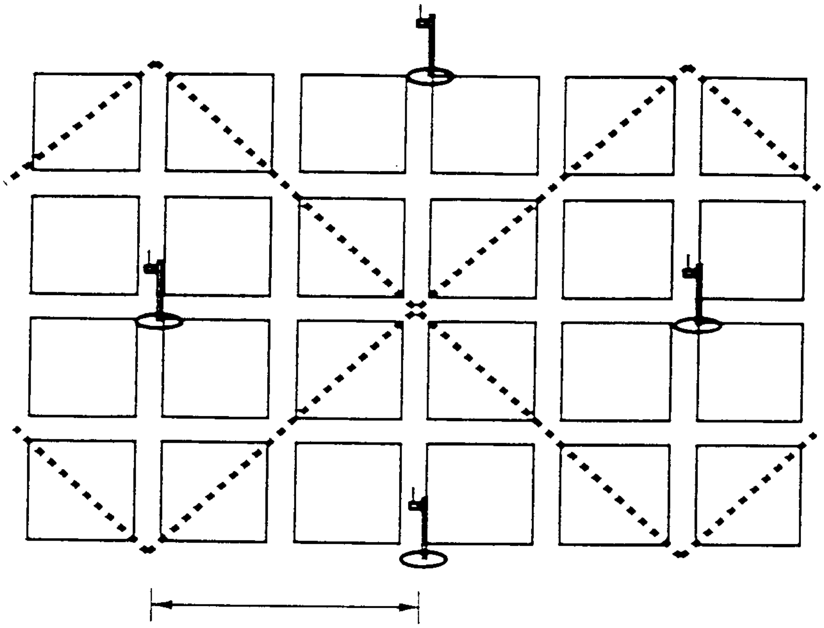

Figure 2. Radio port (RP) locations in a low-tier wireless system.

Design constraints and parameters

The designer of a low-tier wireless network is faced with several design constraints and parameters. These are listed in Table 1.

The constraints are factors that the designer cannot control. They include the characteristics of the customer base to be served, such characteristics as population density and the traffic load that will be offered by each user of the system. Aspects of the physical environment are also constraints. Here these are characterized as the distance between street intersections (both north–south and east–west) in the urban environment and the maximum feasible cell radius. The latter depends on transmitter power, antenna type, building height and construction type, and on radio port antenna height.[4] A further constraint that is externally imposed on the designer is spectrum allocation, the amount of radio spectrum available to be used for the system. This is a decision that is normally made by a government regulatory body.

The design parameters, however, are under the control of the designer. These include the following.

Channel bandwidth is the amount of spectrum occupied by a one-way voice channel. Larger channel bandwidths, eg 30 kHz, can provide higher voice quality, and smaller channel bandwidths, eg 5 kHz, provide lower voice quality.

Cell radius defines the size of a cell's coverage area. It may be no larger than the maximum cell radius described above. Reducing the size of each cell will allow the designer to provide service to more subscribers throughout the service area or to handle more traffic in the service area, but this will also necessitate the installation of more radio ports and consequent higher investment.

Frequency reuse factor defines what fraction of the total number of available channels (in the allocated spectrum) is used in each cell. Generally, use of a higher frequency reuse factor means that co-channel cells will be further apart and co-channel interference will be reduced. On

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[4] Calculation of the maximum feasible cell radius is an interesting radio engineering problem. Relevant issues are discussed in Erceg, V, Ghassemzadeh, S, Taylor, M, Li, D and Shilling, D 'Urban/suburban out-of-sight propagation modeling' *IEEE Communications* 1992 **30** (6) 56–61; Goldsmith, A and Greenstein, L 'A measurement-based model for predicting coverage areas for urban microcells' *IEEE Journal on Selected Areas in Communications* 1993 **11** (7) 1013–1023; and Bertoni, H, Honcharenko, W, Maciel, L and Xia, H 'UHF propagation prediction for wireless personal communications' *Proceedings of the IEEE* 1994 **82** (9) 1333–1359

Table 1. Design constraints and parameters.

Item	Constraint/parameter	Range	Base value
Population density	Constraint	3000–30 000/km^2	
Traffic load per subscriber	Constraint	4–12 ccs	4 ccs
Distance between intersections	Constraint	30–70 m	50 m
Maximum cell radius	Constraint	100–500 m	200 m
Spectrum allocation	Constraint	10–50 MHz	30 MHz
Channel bandwidth	Parameter	5–30 kHz	30 kHz
Cell radius	Parameter	(up to max. cell radius)	
Frequency reuse factor	Parameter	10, 16, 25	16
Grade of service	Parameter	1–5%	2%

the other hand, the smaller number of channels in each cell limits the number of subscribers that can be served and/or the amount of traffic that can be carried within the cell.[5]

Grade of service is the probability that an attempted call will be blocked because all channels in a cell are busy. For example, P.02 service means that there is a 2% probability that a cell will be blocked. Grade of service can be taken as a design constraint, eg P.02 service is the minimum acceptable, or it can be taken as one of the design parameters. Here we adopt the latter view.

For present purposes, we can say that design of a low-tier system involves selection of a value for each of the design parameters. There are trade-offs among the parameters, and only certain combinations of values will provide acceptable service in light of the design constraints. Also, each combination of values implies a required investment to build the system. Here we are interested in the minimum investment needed to provide acceptable service.

In addition to listing the design constraints and parameters, Table 1 also gives the range of values for each that we have considered and the value of each used in our base case.

The model

Our model takes account of these design constraints and parameters in order to compute the required investment to deliver basic telephone service using low-tier wireless technology. The design constraints and parameters are inputs to the model, and the model's output is the required investment per subscriber.

The model considers several factors in order to calculate the cell radius (or, equivalently, the spacing between radio ports) that will be needed in a given situation. This calculation involves a number of steps, each of which will be described.

The spectrum allocation, channel bandwidth, and frequency reuse factor inputs are used to compute the number of channels (pairs) that will be available in each cell. We assume that this number of channels will be used in each cell and that the cost of a radio port is independent of the number of channels it uses. This value, along with the grade of service, is used to compute the amount of traffic (measured in 'hundred call seconds', or ccs) that can be accommodated in each cell.

Subsequently, considering the population density, expected subscription factor, and the expected traffic load per subscriber inputs, the required cell radius is computed. This value may, however, be no greater

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[5] In PACS systems the frequency reuse factor is 16.

Table 2. Equipment costs.

Equipment type	Unit cost range	Unit cost base value
Radio port[a]	US$5000–20 000	US$10 000
Radio port controller unit	US$50 000–150 000	US$75 000
Customer premises equipment	US$100–1000	US$160

[a] The cost of the cable plant required to support a radio port is included in the cost of the radio port.

than the maximum cell radius. It also must be a value that is consistent with the regular placement of RPs within the rectangular street grid as shown in Figure 2.

With the cell radius (and placement of radio ports) known, the investment needed to provide coverage to a known area can be computed. Further, in light of the given population density and subscription factor, the required investment per subscriber can also be computed. These values depend, of course, on the costs of each of the components in the low-tier wireless system. We have investigated low-tier equipment proposed by manufacturers, along with proposed costs, and our estimates of the cost of this equipment that would be incurred by a telephone carrier are shown in Table 2. The table includes both the expected cost range and the cost we have selected for our base case for RPs, RPCUs and CPE. All figures are installed costs and assume that there are large production volumes resulting from a significant demand for this equipment.

Model results

The model results are shown in Figures 3–12. In all cases investment per subscriber is shown as a function of subscription factor. Subscription factors between 0.2 and 0.8, in increments of 0.1, are considered. Results are shown for a variety of assumptions, but, generally, per subscriber investment estimates range from US$200–500.

We present model results for two uniform population densities, 3000 persons per km^2, representing a lightly populated urban area, and

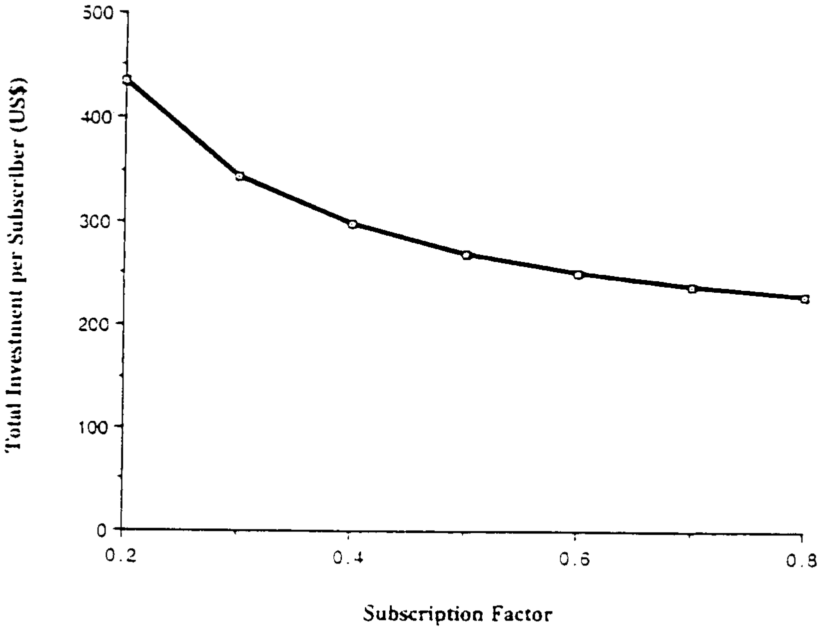

Figure 3. Investment per subscriber for base case assumptions and population density of 3000 persons per km^2.

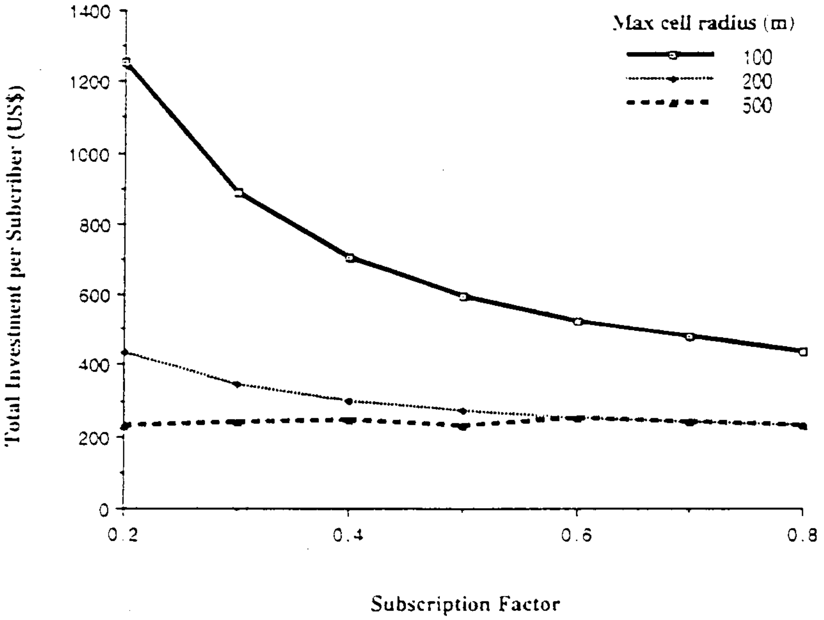

Figure 4. Investment per subscriber for maximum cell radius of 100, 200, and 500 m and population density of 3000 persons per km^2. Otherwise, base case assumptions.

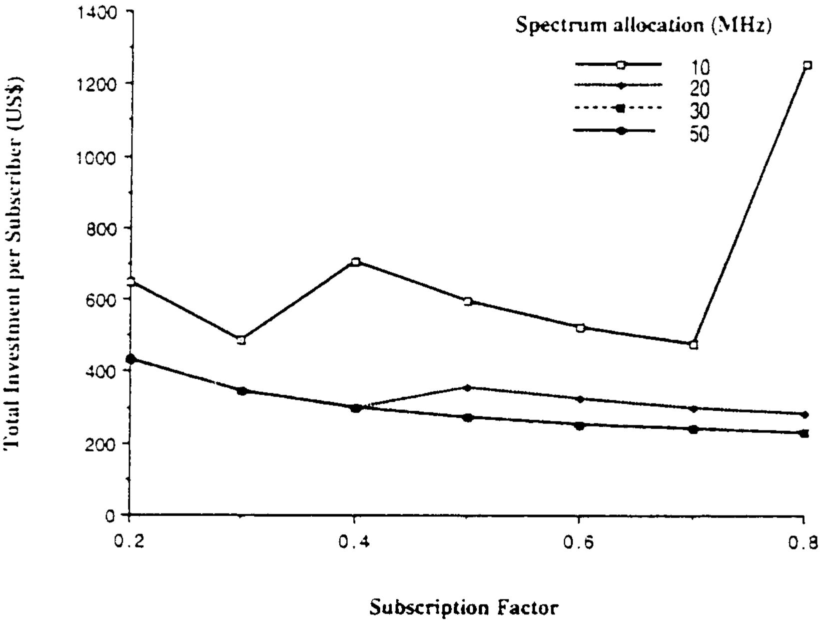

Figure 5. Investment per subscriber for spectrum allocation of 10, 20, 30, and 50 MHz and population density of 3000 persons per km^2. Otherwise, base case assumptions.

30 000 persons per km^2, representing a more heavily populated urban area. Figures 3–6 are based on 3000 persons per km^2. With such a low population density, the placement of RPs is determined primarily by the radio coverage of each RP. Figures 7–11 are based on 30 000 persons per km^2. With such a high population density, the placement of RPs is dictated primarily by the number of radio channels needed to accommodate the traffic originating and terminating in each area.

The model can also be used to test the sensitivity of these results to variations in the design constraints and parameters. The results presented in Figures 4–6 and Figures 8–11 show the effects of such variations.

As shown in Figure 3, for the low density assumption, per subscriber investment falls from US$430 to US$230, as subscription factor increases

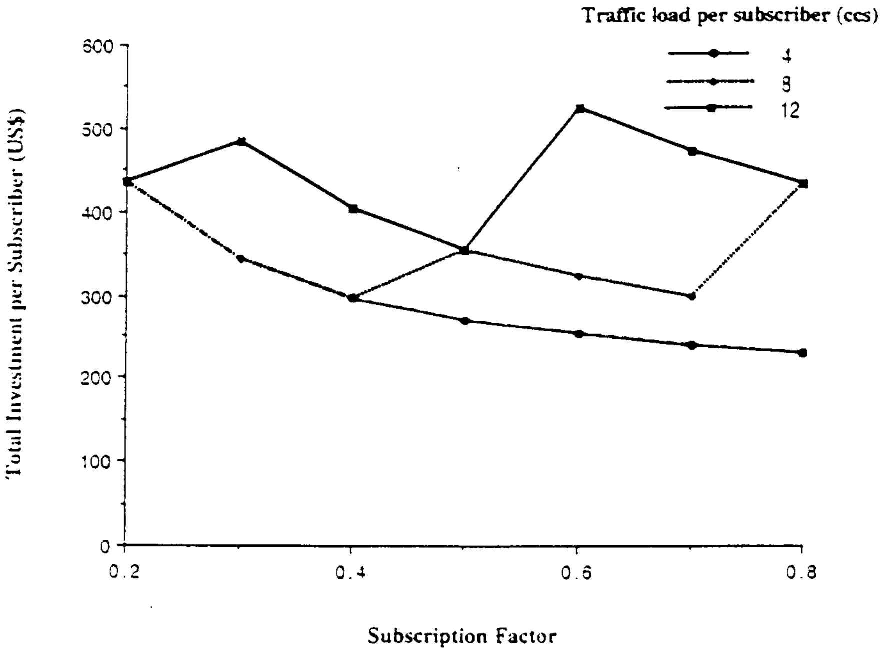

Figure 6. Investment per subscriber for traffic load per subscriber of 4, 8, and 12 ccs and population density of 3000 persons per km^2. Otherwise, base case assumptions.

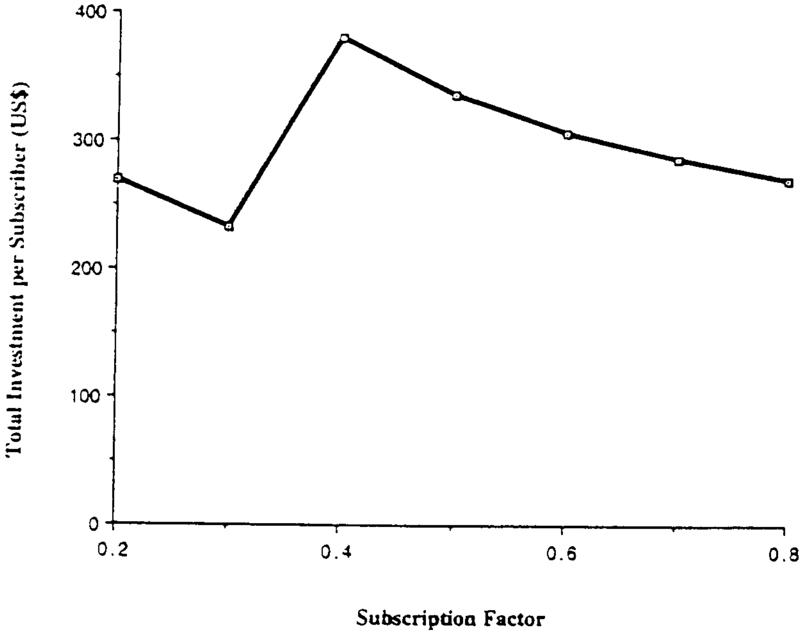

Figure 7. Investment per subscriber for base case assumptions and population density of 30 000 persons per km^2.

from 0.2 to 0.8. Within this range the RP placement remains fixed, and the investment is spread among an increasing number of subscribers, reducing the average investment. These results are insensitive to changes in channel bandwidth, grade of service and frequency reuse factor within the ranges we considered for these variables. This is unsurprising because, at this population density, the RP placement primarily depends on radio coverage considerations. The results are relatively insensitive to the distance between intersections, but per subscriber investment falls slightly with decreasing intersection spacing.

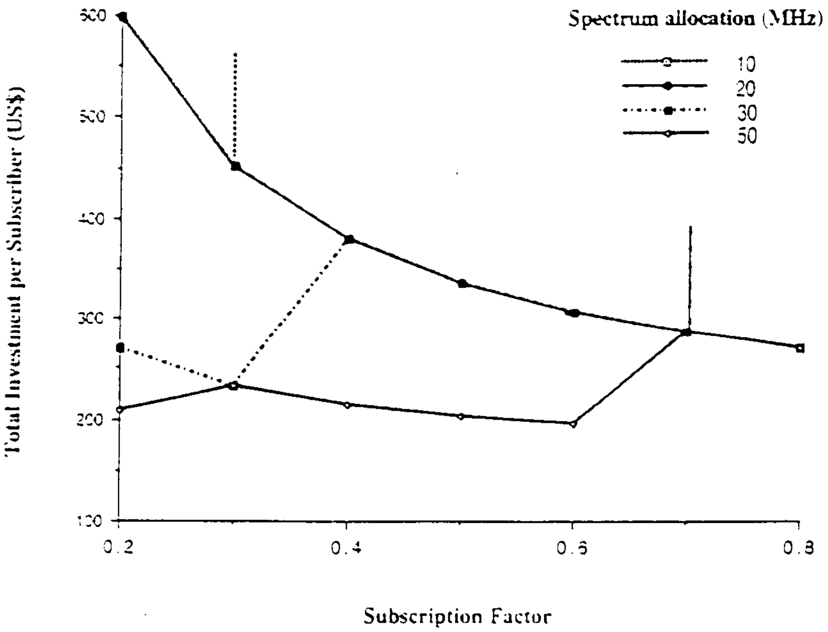

Figure 8. Investment per subscriber for spectrum allocation of 10, 20, 30, and 50 MHz and population density of 30 000 persons per km². Otherwise, base case assumptions.

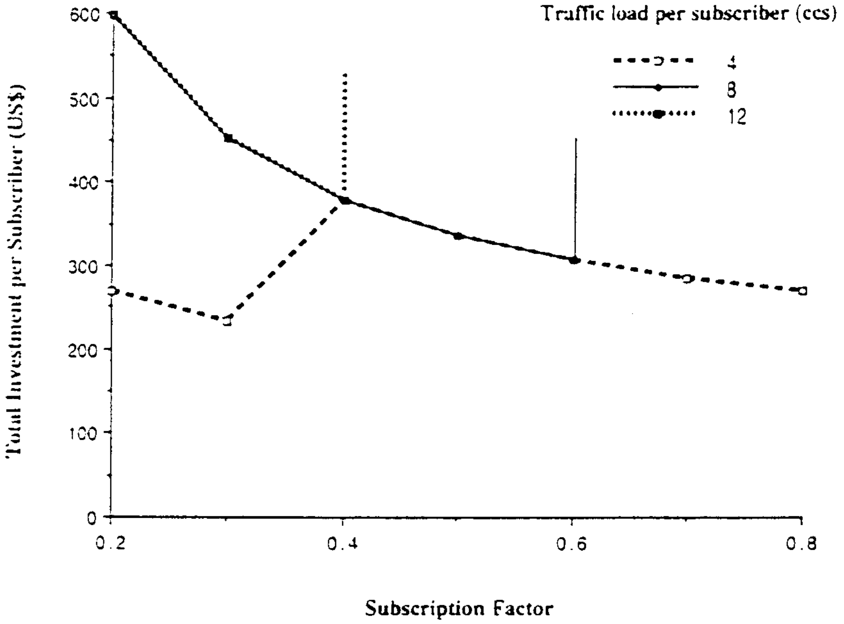

Figure 9. Investment per subscriber for traffic load per subscriber of 4, 8, and 12 ccs and population density of 30 000 persons per km². Otherwise, base case assumptions.

As shown in Figure 4, if radio coverage limits the maximum cell radius to 100 m, many more RPs are needed and per subscriber investment rises dramatically. Similarly, if better radio coverage allows a cell radius of 500 m, fewer RPs are required and per subscriber investment falls.

As Figure 5 shows, even with the low population density assumption, there is a point at which limited spectrum availability requires the use of more RPs and a dramatically higher investment. With our base assumptions, this occurs when the allocated spectrum is less than 20 MHz. Similarly, as shown in Figure 6, high traffic loads require more RPs. As shown, traffic loads per subscriber of 8 and 12 ccs require more RPs and a higher per subscriber investment requirement.

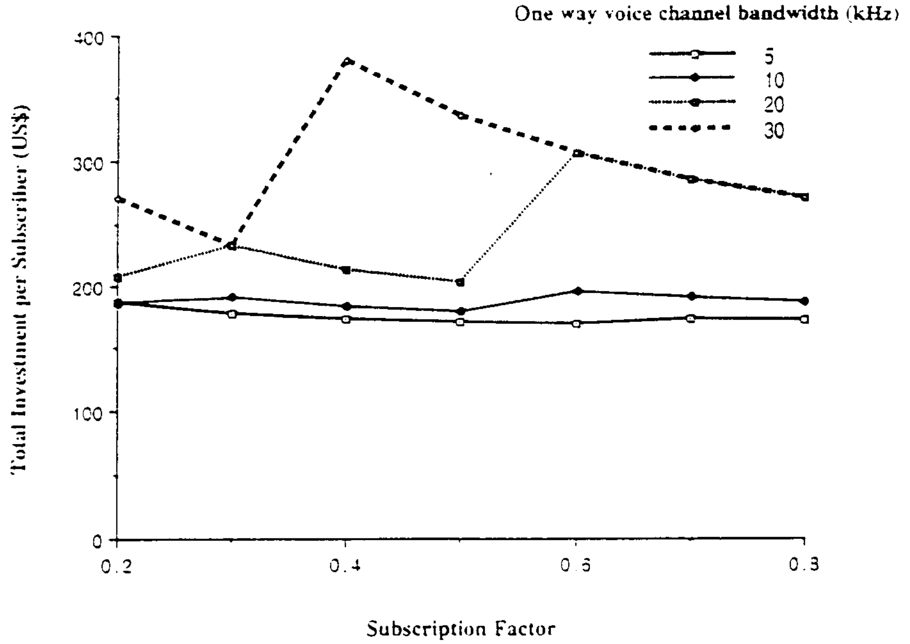

Figure 10. Investment per subscriber for one-way voice channel bandwidth of 5, 10, 20, and 30 kHz and population density of 30 000 persons per km^2. Otherwise, base case assumptions.

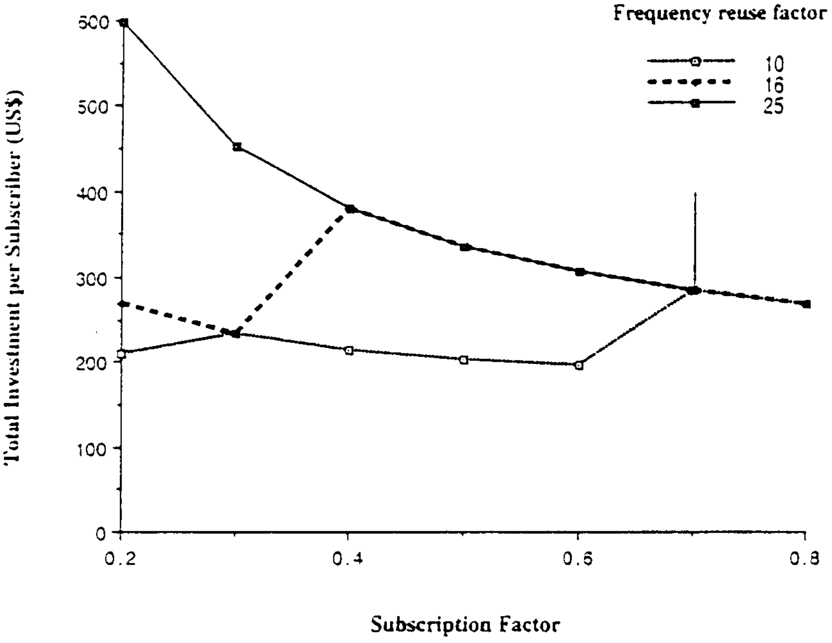

Figure 11. Investment per subscriber for frequency reuse factor of 10, 16, and 25 and population density of 30 000 persons per km^2. Otherwise, base case assumptions.

Generally, one would expect investment per subscriber to decline with increasing subscription factor, as the cost of RPs and RPCUs are averaged among more subscribers, but in Figure 5 and subsequent figures, the per subscriber investment is not always monotonically decreasing. In some cases, the investment per subscriber increases as subscription factors pass through certain values. These increases occur where it is necessary to place an RP every block rather than every second block, or every second block instead of every third block, in order to accommodate all subscribers. The increases are caused by the uniform population density assumption.

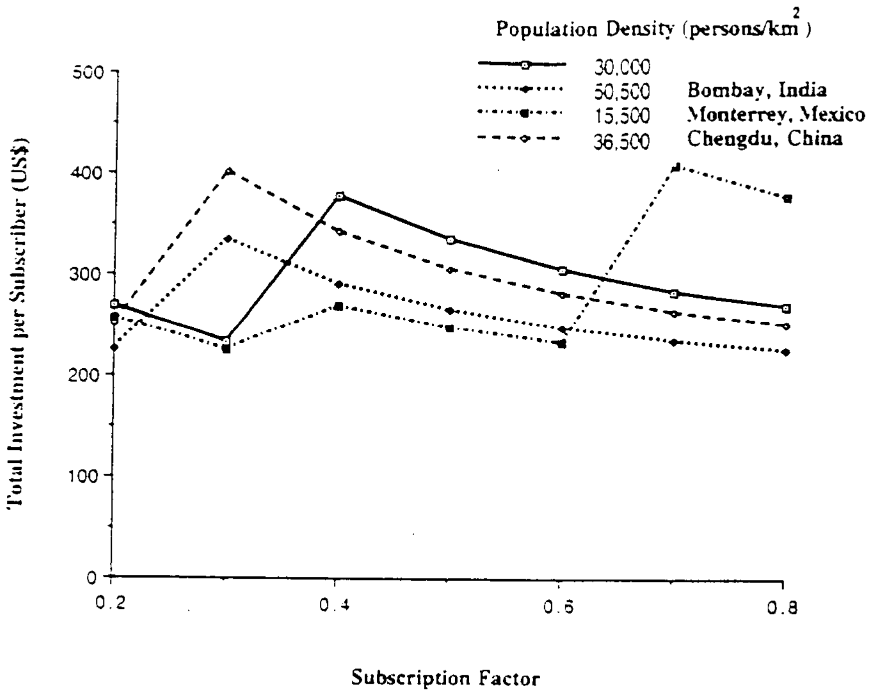

Figure 12. Investment per subscriber for population densities of Monterrey, Mexico, Chengdu, China, Bombay, India, and 30 000 persons per km² and base case assumptions.

This effect is particularly obvious in Figure 7, which shows model results for the higher population density (30 000 persons per km²) more typical of that found in large cities in the developing world. With the higher population density and base case assumptions otherwise, the per subscriber investment varies between US$230 and US$380.

As Figure 8 shows, at the higher population density, changing the amount of spectrum allocated has significant impact on investment per subscriber, which, for example, increases when one reduces the spectrum allocation from 50 MHz to 30 MHz. Further, 10 and 20 MHz spectrum allocations are inadequate for a voice channel bandwidth of 30 kHz. The investment per subscriber for 10 and 20 MHz allocations is substantially higher than for the base 30 MHz assumption at low subscription factors. At higher subscription levels, the spectrum allocations are inadequate to handle all traffic. This is reflected by the 10 MHz curve becoming vertical when the subscription factor reaches 0.3 and the 20 MHz curve becoming vertical when the subscription factor reaches 0.7.

Similarly, high traffic levels can exhaust the available spectrum and lead to an infeasible situation. Figure 9 shows that, with a 30 MHz spectrum allocation, a per subscriber traffic load of 8 ccs cannot be accommodated when the subscription factor is greater than 0.6. Further, a per subscriber traffic load of 12 ccs cannot be accommodated when the subscription factor is greater than 0.4.

Figure 10 shows that investment per subscriber can be reduced by decreasing the average one-way channel bandwidth. Channel bandwidths of 5 and 10 kHz allow many more channels per radio port than a 30 kHz bandwidth. This allows use of fewer radio ports, resulting in a smaller investment. The use of a smaller channel bandwidth, however, will result in a considerable reduction in speech quality, removing an advantage associated with low-tier wireless systems. Such a reduction in quality may be inadvisable in a system intended to replace a wireline telephone system.

The model suggests that a wide range of frequency reuse factors yield similar per subscriber investment, but, using the higher population density and base assumptions otherwise, a reuse factor of 25 allows too few channels in each cell. This requires the need for more RPs and consequent higher investment. At subscription factors greater than 0.7, it is impossible to serve all traffic with one RP for each block. This is reflected by the curve for a reuse factor of 25 becoming vertical in Figure 11.

We have also considered population densities (in persons per km^2) corresponding to those found in three developing world cities: Monterrey, Mexico (15 500); Chengdu, China (36 500); and Bombay, India (50 500). The per subscriber investment results for these population densities, shown in Figure 12, are similar to the assumption of 30 000 persons per km^2. This suggests that wireless service may be attractive in a variety of densely populated developing world cities.

The model results are also sensitive to equipment cost assumptions. Since each subscriber needs a CPE unit, the per subscriber investment increases dollar for dollar with changes in the CPE cost. The remaining portion of per subscriber investment is strongly dependent on RP cost and will increase or decrease with changes in this cost. Actual equipment costs will be known only when manufacturers begin to sell equipment and reach significant production volumes.

The results shown in Figures 3–12 should be compared with the investment required to build conventional cable-based outside plant. Available studies indicate that, in the US, this value is in the range of US$700–1200 per subscriber.[6] Required outside plant investment in the developing world is more difficult to establish because of the inconsistency with which data is reported. Recognizing that a significant portion of outside plant investment is comprised of capitalized labor cost, and considering reported labor rates in developing nations,[7] we estimate that outside plant investment (including inside wire and CPE) in the developing world has a lower bound of approximately US$500 per subscriber. It may be significantly higher than this figure. We have included inside wire and CPE in this estimate in order to make it directly comparable with the model results, which includes the (considerably higher) cost of the wireless CPE.

The model results indicate that the required investment for a low-tier wireless system is likely to be significantly lower than the investment in a telephone network using conventional outside plant. The results are particularly compelling for high subscription factors, large maximum cell radii, spectrum allocations of 30 MHz or greater, low traffic levels and low channel bandwidths.

Conclusion

Our primary conclusion is that wireless technology does indeed offer an attractive alternative for the delivery of basic telephone service in the developing world. It can be deployed rapidly, it requires little heavy construction, and, as shown by this work, its required investment compares very favorably with that of conventional outside plant. Our investment estimates of US$200–500 per subscriber are substantially less than typical values for cable-based systems.

[6] See, for example, Armstrong, T and Fuhr, J 'Cost considerations for rural telephone service' *Telecommunications Policy* 1993 17 (1) 80–83

[7] International Telecommunications Union *ITU Yearbook of Statistics* ITU, Geneva (1992); OECD *Communications Outlook* OECD, Paris (1993)

While radio coverage is critical at low population densities, at densities typical of large cities in the developing world, traffic carrying capacity is a more important design issue. Accordingly, policy-makers should carefully consider spectrum allocation for wireless local loop systems in light of projected traffic loads and expected voice channel bandwidths. Our results suggest that, if one wishes to use 30 kHz voice channels to provide high quality audio, a spectrum allocation of at least 30 MHz for the service is appropriate. Smaller spectrum allocations may result in higher than necessary investments by carriers. Depending on actual traffic levels, more than 30 MHz may be required.

We observe no significant economies of scale inherent in a wireless approach to basic telephony. Plots of investment per subscriber vs subscription factor are relatively flat, except where it is necessary to decrease spacing between RPs. This result suggests that the service does not have the characteristics of a natural monopoly and that a competitive industry structure is feasible. Accordingly, policy-makers should consider low entry barriers for this service. Further work is needed to determine how many carriers might efficiently operate in the same market and how much spectrum should be allocated to each.

Our work shows that the required investment and the capacity of a wireless telephone system are dependent on such design parameters as frequency reuse factor, channel bandwidth, cell radius and grade of service. The use of a modeling tool like the one described here may be valuable in the selection of such parameter values.

The cost of RPs and CPE represents a large fraction of the investment needed to build a wireless system like the type described here. National governments and telephone carriers may wish to consider what actions they might take to insure that large production volumes will lead to low RP and CPE cost. Standardization and aggregation of demand among several nations or carriers may help to achieve such production volumes.

Many of the issues raised here need to be explored more carefully, both from a policy perspective and from a system design perspective. The very large need for basic telephone service in the developing world, along with the apparent ability of wireless technology to meet the need, suggests the importance of such careful work, which can result in a set of national policies and an equipment design specifically tailored to meet developing world needs.