WiMAX Deployments with Self-Installable Indoor Terminals

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Introduction

The ability to support the deployment of indoor customer-installable end-user terminals can provide operators significant cost savings that can greatly enhance the business case for a WiMAX fixed broadband wireless network. For the same operational performance, indoor terminals will be less expensive since they do not need to be hardened to deal with the more stringent requirements of outdoor environments and they can be designed as a single-box solution thus eliminating extensive cabling and the need for multiple packages. And more importantly indoor units do not require professional roof-top installation. The net savings in CPE costs for the operator can amount to several hundred dollars per customer.

This CPE cost savings however, does not come without other offsetting infrastructure costs that must be considered when making network deployment decisions. This paper will provide some insights as to the trade-offs that need to be considered and offer some deployment guidelines to help assure a winning business case when planning and deploying a WiMAX fixed wireless network with indoor self-installable customer terminals.

Projected CPE Costs

Recognizing the need for low cost residential customer terminals, WiMAX vendors are aggressively pursuing designs and manufacturing approaches that are intended to drive down prices. Since WiMAX solutions are based on the worldwide IEEE 802.16 standard, ASICs and other critical components will be available at costs that will quickly decline with increasing volume. For the purposes of the analyses that follow later in this paper outdoor terminal prices are assumed be about $350[1] and indoor terminals about 30% less. With growing volumes and increased manufacturing efficiencies, these prices are projected to decline approximately 20% per year and 30% per year respectively.

Installation costs for operator-installed outdoor terminals requiring a truck-roll can vary considerably from region to region depending on local labor rates, installation

[1] Terminal prices will vary case-by-case in accordance volume discounts, feature-set, etc. $350 is an aggressive pricing assumption based on a minimal feature-set required for residential applications and a volume purchase discount typical for a large operator. The 30% differential for indoor terminals seems reasonable based on savings related to packaging and reduced environmental requirements.

complexities, and roundtrip travel times. The following figure provides a forward looking summary of projected average selling prices (ASPs) for residential WiMAX terminals and projected cost savings for self-installed indoor terminals assuming an installation cost differential of $150 in 2005 growing at 5% per year in future years. The net cost differential of approximately $250, as opposed to the absolute terminal pricing is the key variable in quantifying the trade-offs between the various deployment options.

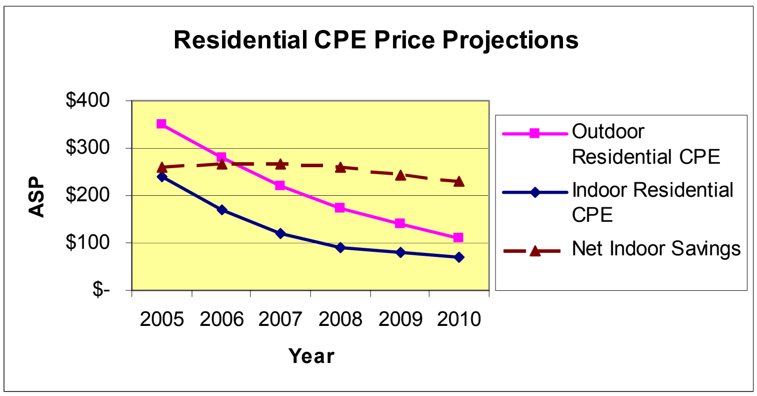


Figure 1: Residential Terminal Projected Prices

Performance Factors

From the end-customer's perspective the functionality of indoor and outdoor terminals will be the same, however due to reduced system gain and increased path losses the range capability of indoor terminals will always be less than the range capability for outdoor terminals. Professionally installed outdoor terminals will be mounted on a roof top or under the eaves. These units will have a high gain, narrow beam-width antenna and when mounted, will be strategically located on the customer premises and carefully aligned so as to maximize received signal strength and minimize the effects of interference.

Indoor residential terminals on the other hand will be subject to the following limitations:

- Indoor units will have lower antenna gain (wider beam width) to reduce the size of the unit and to facilitate self-installation. This results in a reduced system gain of approximately 6 dB.

- Signals will have to pass through one or more walls or windows: Signal loss through walls and windows is caused by a combination of signal reflections and signal attenuation as it passes through the medium and is more significant at shorter wavelengths. At frequencies in the 2.5 to 5.8 GHz range these losses can be significant.

- Self-installable indoor terminals are subject to customer-by-customer installation variations that will not always be optimal. Installations for example, will typically be such that the height of the terminal relative to the height of the base station antenna will result in an installation that is off bore-sight to the base station antenna in the elevation plane.

Based on the current WiMAX channel model[2] and terrain type; a 6 dB reduction in system gain and the anticipated excess path losses for indoor units will result in a range reduction compared to installation with outdoor units of 65% to almost 75%. As a result, in both capacity-limited and range-limited deployments, the use of indoor terminals will require additional base station infrastructure to make up for the reduced channel capacity and/or range. The cost of this additional network infrastructure must be taken into consideration when making deployment decisions.

The operator has the following deployment alternatives from which to choose:

1. Deploy base station infrastructure to support 100% outdoor residential terminals only.

2. Deploy base station infrastructure to support 100% indoor residential terminals only.

3. Deploy base station infrastructure assuming a mix of indoor and outdoor terminals.

In the following sections these three alternative deployment approaches will be analyzed with the intent of providing the reader with a quantitative comparison of the alternatives.

Channel and Base Station Capacity

To quantitatively evaluate the relative trade-offs between the deployment options it is necessary to understand the relationship between downlink (DL) channel capacity of a WiMAX base station and the coverage area or range over which the base station is expected to operate. Since fixed WiMAX deployments use adaptive modulation and adaptive coding, the effective DL channel capacity is dependent on the mix of

[2] Erceg, et al, Channel Models for Fixed Wireless Applications, IEEE 802.16 Broadband Wireless Access Working Group, February 23, 2001

modulations and the distribution of active users over the coverage area.[3] For the purpose of this discussion a WiMAX-compliant solution with the characteristics summarized in table 1 will be assumed. The most important parameters, system gain and BW efficiency, are consistent with mid-performance[4] WiMAX-compliant solutions, based on IEEE 802.16-2004, that are expected to be available in the near future.

WiMAX Radio Characteristics for Downlink Range and Capacity Estimation	
Frequency Band	3.5 GHz
Duplexing	Frequency Division Duplexing (FDD)
Channel Bandwidth	3.5 MHz
Adaptive Modulation	BPSK, QPSK, 16QAM, 64QAM (COFDM)
BW Efficiency	2.8 bits per HZ (net of PHY and MAC overhead)
Downlink User Data Rate	9.7 Mbps at 64QAM to 1.1 Mbps at BPSK
Propagation Conditions	100% of Users Non-Line-of-Sight (non-LOS), uniformly distributed over the base station coverage area
Downlink System Gain for Outdoor CPEs	164 dB at BPSK
Downlink System Gain for Indoor CPEs	158 dB at BPSK
Excess Path Loss for Indoor CPEs	14 dB

Table 1: Base Station Radio Characteristics

Based on these characteristics and assuming a uniform distribution of active non-line-of-sight users over the coverage area it is possible to determine the effective base station downlink channel capacity for the three CPE deployment options: all outdoor, all indoor and mixed indoor and outdoor. This is shown in figure 2 with range projections based on a typical urban environment (terrain category “A”). The range notations used in figure 2 are described in table 2.

[3] For further discussion on this topic see WiMAX White Paper “WiMAX Deployment Considerations for Fixed Wireless Access in the 2.5 GHz and 3.5 GHz Licensed Bands”, May, 2005.
[4] The IEEE 802.16-2004 standard includes optional link budget extension modes and the WiMAX Forum has defined three performance profiles for fixed applications. In the “Extended” profile the use of Base Station Adaptive Antenna Systems (AAS), for example, can add several dB to the link budget as compared to that shown in table 1. Since the increased range applies to both indoor and outdoor terminals relative ration between the two essentially the same.

Range Notation	Description
"a"	Range limit for deployments comprised solely of indoor self-installable terminal
"b"	Range at which modulation/code rate changes from 64QAM-3/4 to 64QAM-2/3 for outdoor terminals. Deployments with all outdoor terminals limited to this range will assure maximum DL channel capacity.
"c"	At this range there is a secondary peak in the channel capacity for the mixed deployment scenario. This is the point at which the mix of indoor and outdoor terminals distributed over the coverage area is "optimal".
"d"	This is the maximum range for fixed outdoor terminals. Most fixed wireless metro deployments will be capacity-limited rather than range-limited unless the operator has a significant amount of spectrum.
"e"	Deployments limited to this range or less assures that all users are operating at 64QAM-3/4 code rate, even if all are indoor terminals, thus achieving maximum downlink channel capacity. Deploying base stations with this range limitation is generally not a viable deployment option since the combination of household density and the market penetration is unrealistically high.

Table 2: Description for Range Notations

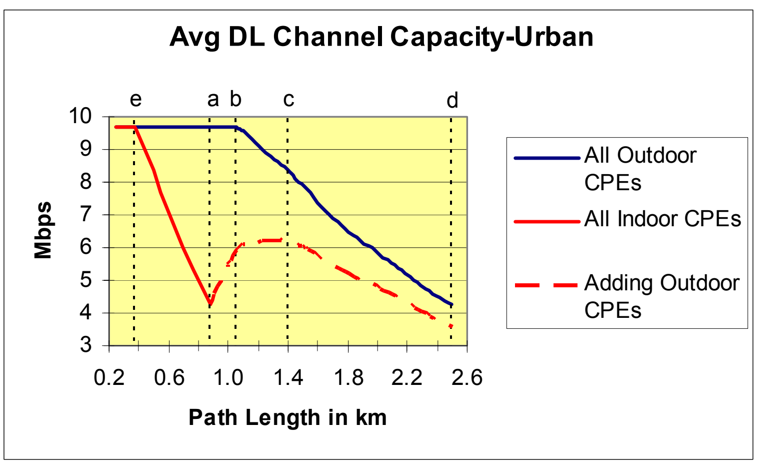


Figure 2: Average Downlink Channel Capacity

Converting the downlink channel capacity to the number of potential customers that can be supported provides additional insight as to the infrastructure cost implications. For a residential-only customer base using the service characterization[5] summarized in table 2, the channel capacity can be expressed in terms of the number of supportable customers per channel as shown in figure 3 for ranges, "a", "b", "c", and "d"; "d" denoting maximum range.

Service	DL Data Rate	Overbooking Factor
Residential Internet Access	384 kbps Average	20:1
Residential VOIP	128 kbps	4:1
Customer Breakdown	50% Internet Access Only 50% Internet Access plus VOIP	

Table 3: Residential Service Definition

The service definitions in table 3 convert to an average data rate of 35 kbps per residential customer or approximately 28 residential broadband customers per megabit of channel capacity. When deploying with indoor CPEs, figure 3 suggests a mixed deployment of indoor and outdoor CPEs, at ranges "b" or "c", will provide a greater revenue potential per channel or alternatively, a lower base station infrastructure cost per subscriber.

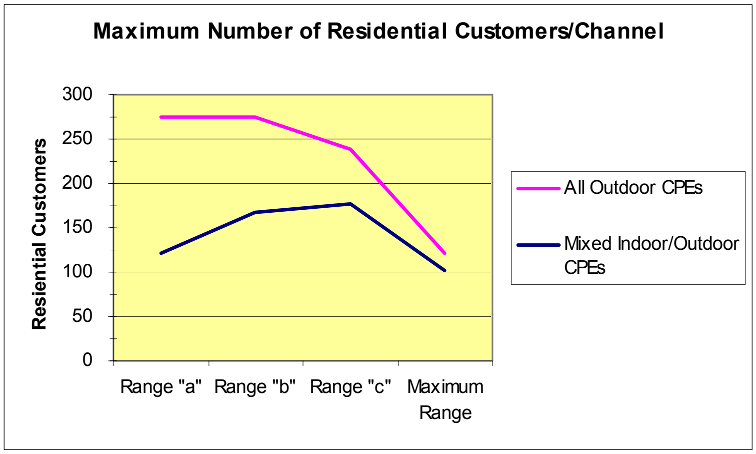


Figure 3: Residential Customer Capacity per Channel

[5] The values assumed for services and overbooking factors are for illustrative purposes. In practice these values will vary from operator to operator and in many cases a number of service level packages will be offered by the operator with varied committed and peak information rates.

Deployment Examples

In this section some deployment examples will be analyzed in order to quantify the relative trade-offs and potential cost benefits that can be realized with the deployment of indoor CPEs. This analysis requires some assumptions on equipment and base station infrastructure costs. Base station infrastructure costs can be broken down into a fixed cost component that includes acquisition costs, civil works, and backhaul and a variable cost component, which, in this case, is the WiMAX point-to-multipoint equipment. Both of these price components can vary considerably from solution to solution and the particular deployment approach taken by the operator. For the purposes of this exercise a range of values are assumed for the base station infrastructure cost as summarized in table 4. A range of values is also assumed for the savings realized when deploying lower cost indoor terminals relative to outdoor terminals. Although figure 1 suggests a $250 cost differential for terminals, it is reasonable to expect that, in some situations, installation costs will be lower and there is also the possibility that outdoor terminals will experience more aggressive price reductions than is indicated in figure 1. In any case, a $50 price differential for terminals provides a low end benchmark. Outdoor terminal installations in rural areas are likely to be a bit more expensive due to the additional travel time, hence the $50 add-on.

CAPEX Item	Low End	High End
Base Station "Fixed" Costs (Civil works, Backhaul, etc.)	$15K	$75K
Base Station "Variable" Costs (WiMAX Equipment)	$5K per Channel	$10K per Channel
Outdoor CPE Cost minus Indoor CPE Cost (Including installation difference)	$50 per Subscriber (Plus $50 for rural installs)	$250 per Subscriber (Plus $50 for rural installs)

Table 4: CAPEX Assumptions for Deployment Examples

Table 5 provides the demographic assumptions that are used for the four deployment examples that follow. In each scenario the base-line configuration assumes an all-outdoor deployment approach. Deploying with all outdoor terminals requires the least number of base stations and/or channels and therefore, represents the lowest base station infrastructure investment. In capacity-limited deployments with indoor terminals, additional base stations and/or additional channels are required to make up the capacity difference. And if the operator's goal is to deploy with 100% indoor terminals, the deployment often becomes a range-limited one which, in most cases results in a base station infrastructure with excess capacity. The added infrastructure cost when deploying with indoor terminals will offset some of the savings in terminal cost. The following examples will provide a more quantitative view of the net CAPEX differences.

Scenario	Coverage Area	Subscriber Density	Base Line Infrastructure
1	60 sq-km, Terrain Category A (Urban)	250 Subscribers/sq-km	4-Channel Base Station deployment with all outdoor CPEs
2		375 Subscribers/sq-km	
3		600 Subscribers/sq-km	6-Channel Base Station deployment with all outdoor CPEs
4	60 sq-km, Terrain Category C (Rural)	50 Subscribers/sq-km	3-Channel Base Station deployment with all outdoor CPEs

Table 5: Demographic Assumptions for Deployment Examples

Scenario 1: In this example it is assumed that all of the base station configurations are limited to 4 channels. In practice, this could be a limitation imposed by the lack of access to sufficient spectrum to deploy additional base station channels. That being the case, the only way to increase capacity is by deploying additional base stations. The assumed subscriber density of 250 subscribers per sq-km requires a data density over the 60 sq-km coverage area of approximately 5 Mbps/sq-km to meet the residential service requirements defined in table 3. As shown in figure 4, to deploy with 100% indoor CPEs the coverage area of each base station will have to be limited to 2 sq-km (vertical dashed line “a”). This is approximately one-third the coverage area for a base station deployment with all outdoor CPEs. Limiting the base station range to “b” or “c” for a mixed indoor/outdoor CPE deployment results in a coverage area of approximately 3 and 5 sq-km respectively.

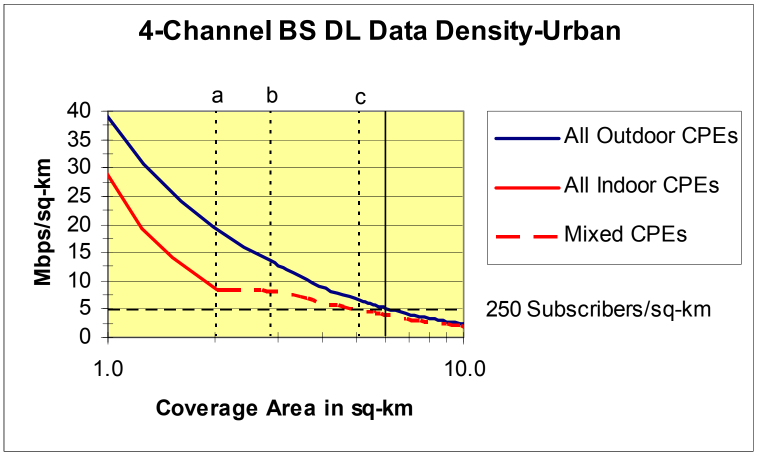
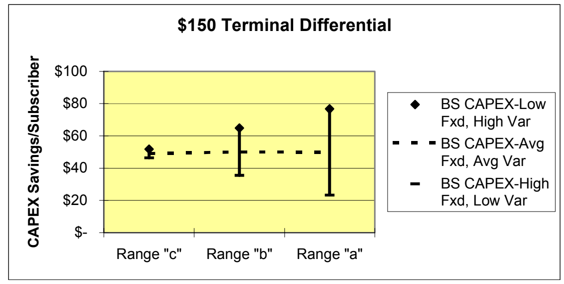


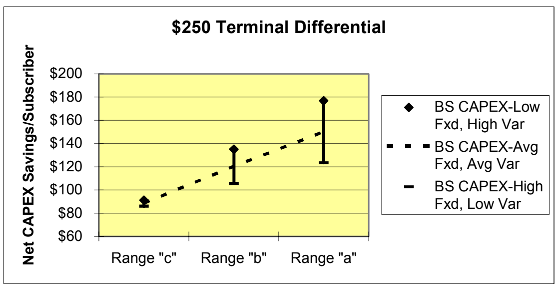
Figure 4: Downlink Data Density for Scenario 1

The results for scenario 1 are summarized in figure 5. At the $250 terminal price differential there is a clear advantage in a range-limited base station deployment to support an all-indoor CPE deployment independent of which base station CAPEX component dominates the infrastructure cost. Additionally, there is also considerable excess capacity when limiting the range to either "a" or "b". This excess capacity also has economic benefit in that it enables the operator to support additional customers or alternatively, to offer enhanced services to the existing customer base. In either case the operator has the potential for additional revenues without having to invest in additional base station infrastructure.

In this scenario, with the indoor to outdoor price differential at the low end of the $50 to $250 range, there is a net CAPEX penalty when limiting the base station range to support a high percentage of indoor CPEs and there is a marginal CAPEX benefit when limiting the range to "c". At the intermediate CPE price differential of $150 there is, on "average", a CAPEX benefit of approximately $50 per subscriber for a base station range limited at "a", "b", or "c". If base station fixed CAPEX dominates the infrastructure cost however, the preferred range would be "c", whereas if variable costs dominate the preferred range would be "a".

Scenario 1 - Urban	All Outdoor	Range "c"	Range "b"	Range "a"
Per Cent Indoor CPEs	0%	39%	70%	100%
Total Subscribers	15,000	15,000	15,000	15,000
Base Stations	10	12	21	30
Channels per BS	4	4	4	4
Capacity for Add'l Subscribers	747	382	7,062	7,611





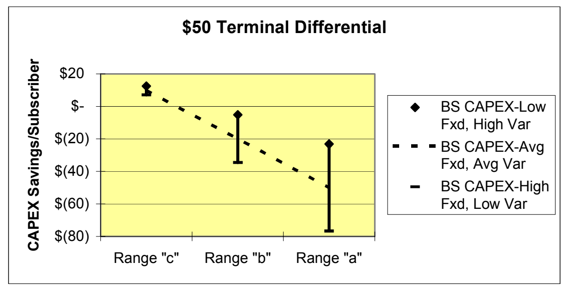


Figure 5: Summary for Scenario 1

Scenario 2: This example assumes a higher customer density of 375 subscribers per sq-km resulting in a data density requirement of 7.5 mbps per sq-km. In this scenario it is assumed that there is sufficient spectrum to increase the channels to at least 6 per base station to support the deployment of indoor CPEs. As figure 6 indicates, a 6-channel base station with mixed indoor and outdoor CPEs closely matches the capacity of a 4-channel base station with all outdoor CPEs at range "c".

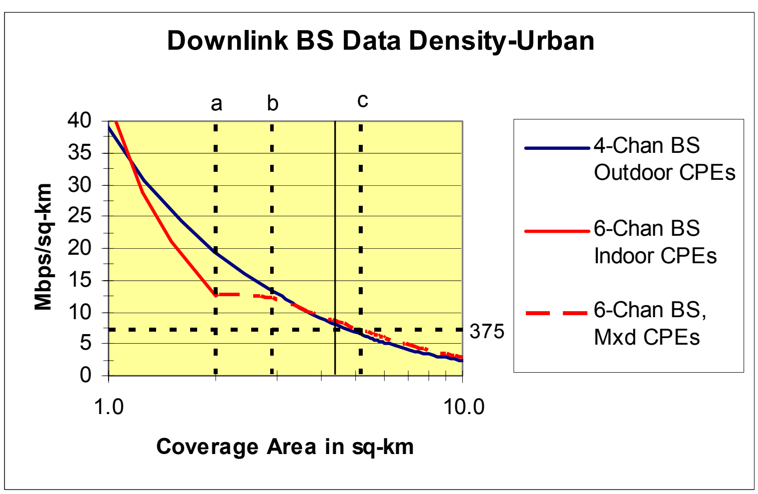
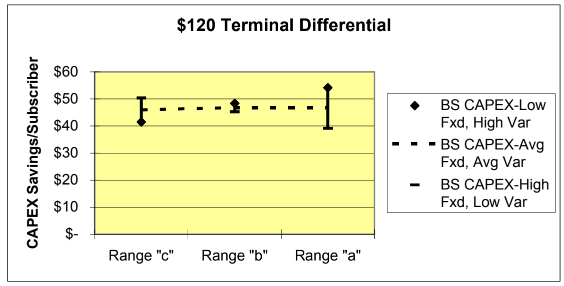
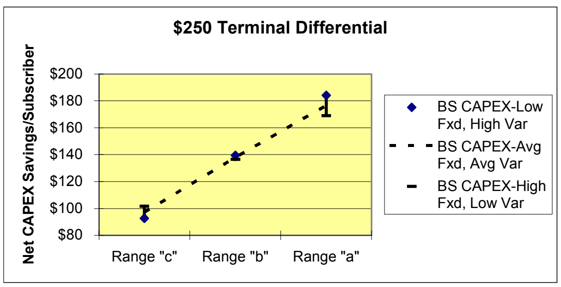


Figure 6: Downlink Data Density for Scenario 2

The results for scenario 2 are summarized in figure 7. As with the previous example, with an indoor to outdoor CPE price differential of $250, the maximum CAPEX savings per subscriber occurs when the base station range is limited to range “a” thus supporting 100% indoor CPEs. While with a $50 price differential the breakeven point occurs when the base station range is limited to “b”, supporting 70% indoor CPE deployment.

Scenario 2 - Urban	All Outdoor	Range "c"	Range "b"	Range "a"
Per Cent Indoor CPEs	0%	39%	70%	100%
Total Subscribers	22,500	22,500	22,500	22,500
Base Stations	14	12	21	30
Channels per BS	4	6	6	6
Capacity for Add'l Subscribers	2,078	388	10,610	11,434





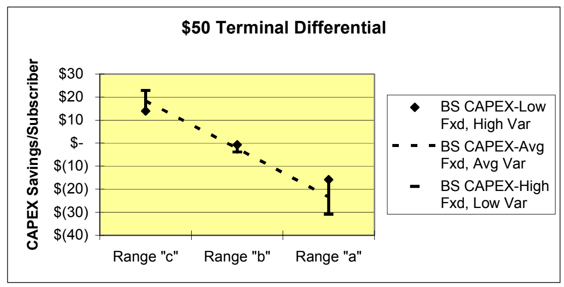


Figure 7: Summary for Scenario 2

Scenario 3: This urban scenario is essentially an extension of scenario 2. The number of base stations for each deployment alternative is the same as in scenario 2 and only base station channels added where needed to support a higher customer density of 600 subscribers per sq-km. For this scenario, the required downlink data density is approximately 12 Mbps/sq-km. This requires two additional channels per base station for the all-outdoor CPE deployment and three additional channels per base station for the mixed CPE case for a range limited to “c”. For the range “a” and “b” alternatives, the higher subscriber density simply consumes most of the excess capacity that was present in scenario 2.

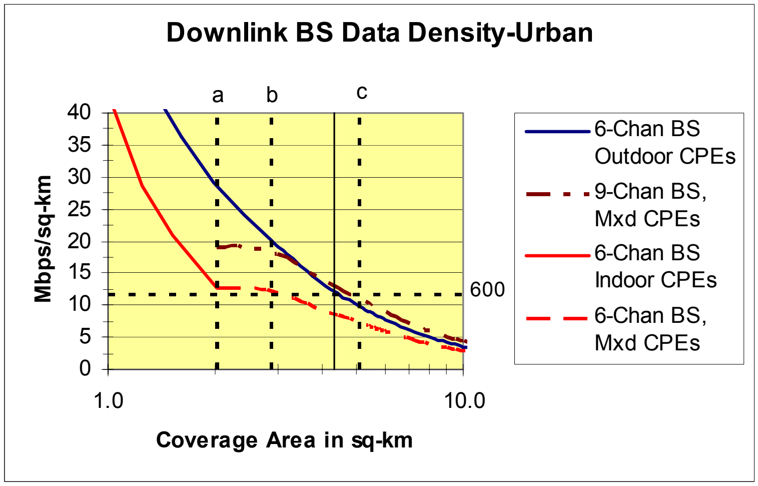
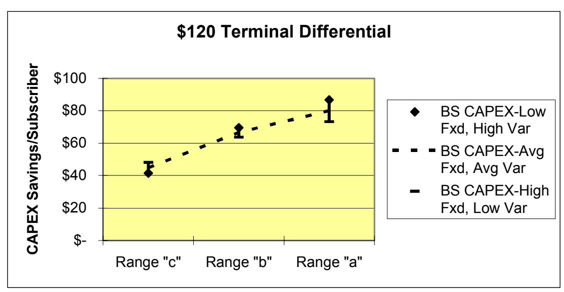
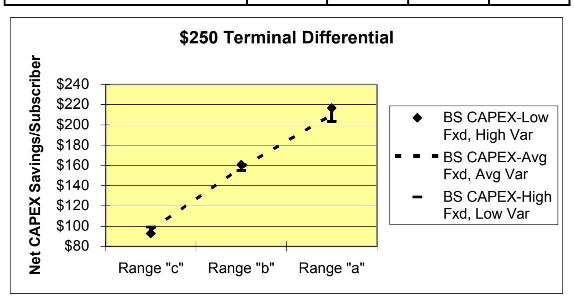


Figure 8: Downlink Data Density for Scenario 3

A summary for scenario 3 is provided in figure 9. As with the previous two examples, with a $250 price differential, there is a significant CAPEX benefit with a range-limited deployment that supports 100% indoor CPEs. With a $50 CPE price differential, the ratio of fixed to variable base station costs plays a bigger role in determining the most cost-effective deployment alternative. An additional consideration if the range "c" alternative is selected is the availability and potential cost of the added spectrum required to deploy base stations with nine channels versus the six channels required if the range "b" alternative is implemented.

Scenario 3 - Urban	All Outdoor	Range "c"	Range "b"	Range "a"
Per Cent Indoor CPEs	0%	39%	70%	100%
Total Subscribers	36,000	36,000	36,000	36,000
Base Stations	14	12	21	30
Channels per BS	6	9	6	6
Capacity for Add'l Subscribers	1,191	1,824	1,486	2,310





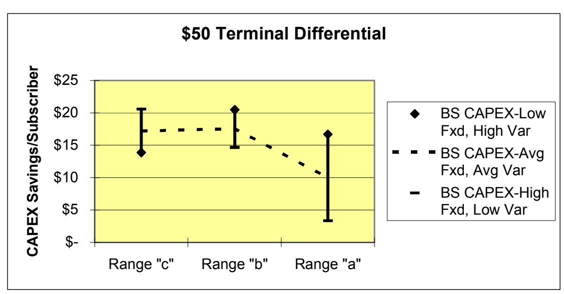


Figure 9: Summary for Scenario 3

Scenario 4: This example is for a rural environment with a relatively low customer density requirement of approximately 0.6 Mbps/sq-km to support 30 subscribers per sq-km.

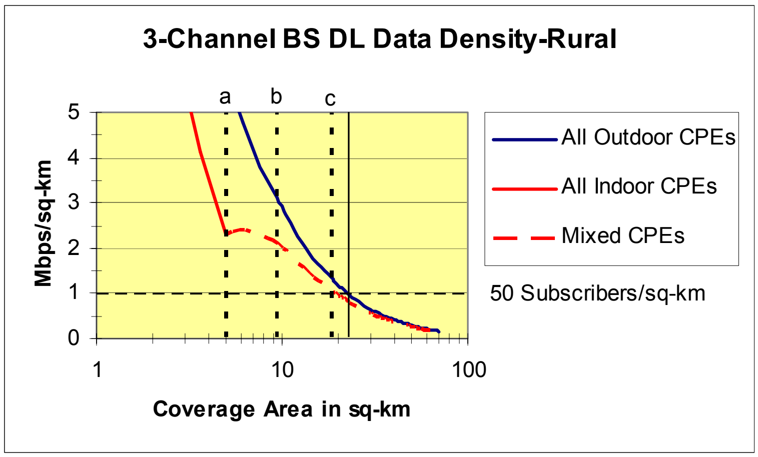
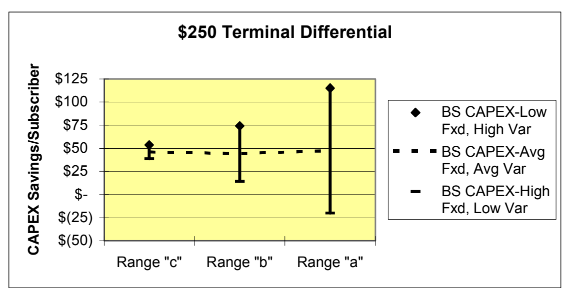
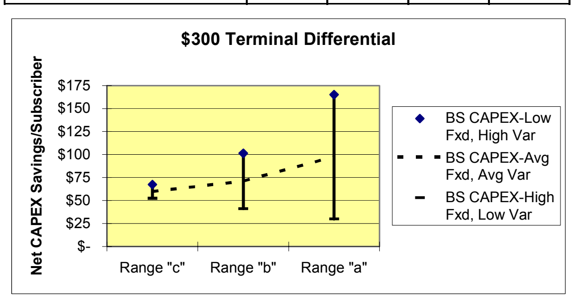


Figure 10: Downlink Density for Scenario 4 – Rural

The results for this scenario are summarized in figure 11. In this case the added base station infrastructure essentially eliminates the terminal savings. With a $250 price differential there is some net CAPEX savings if the fixed base station costs are at the low end of the range, otherwise there is no net gain, and it most cases, a loss, by deploying with indoor units for this scenario.

Scenario 4 - Rural	All Outdoor	Range "c"	Range "b"	Range "a"
Per Cent Indoor CPEs	0%	27%	54%	100%
Total Subscribers	3,000	3,000	3,000	3,000
Base Stations	3	4	7	12
Channels per BS	3	3	3	3
Capacity for Add'l Subscribers	409	726	3,852	2,775





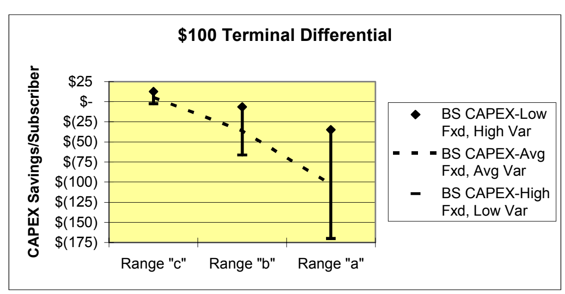


Figure 11: Summary for Scenario 4

Generic Comparison of Terrain Categories

Terrain category "A" was assumed for the first three urban scenarios and terrain category "C" for the rural environment, scenario 4. Figure 12 shows the relationship for per cent indoor CPEs and deployed coverage relative to the maximum coverage for all three terrain categories. The points representing ranges "b" and "c" are also included in the graph. This set of curves can be used to estimate the number of additional base stations that need to be deployed to increase the percentage of indoor CPEs.

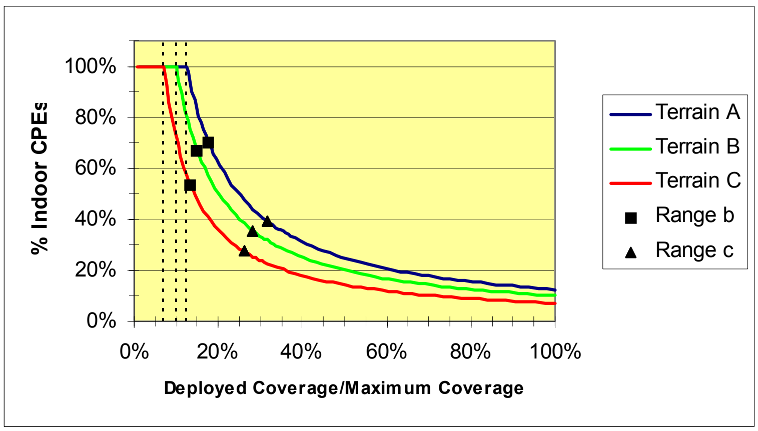


Figure 12: Percent Indoor CPEs vs. % of Maximum Coverage Area

The curves in figure 13 show the relationship between downlink data density per base station channel and the deployed coverage area.

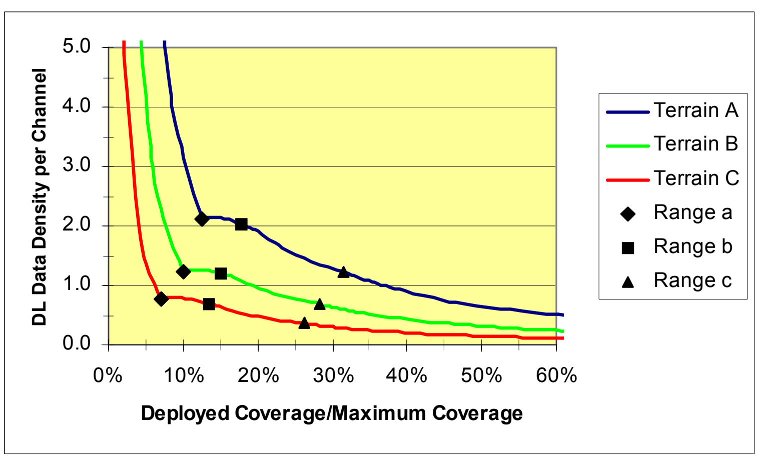


Figure 13: Downlink Data Density per Channel vs. % of Maximum Coverage Area

The following table provides a summary of the expected range and coverage area for the three terrain categories with a +/- 6 dB variation in system gain. The range estimates are based on the Erceg, et al, propagation model cited earlier in this paper and assumes outdoor non line-of-sight customer terminals. The base station spacing and estimated coverage assumes a hexagonally shaped coverage area for each base station.

Terrain Category	System Gain	BPSK Outdoor CPE Range	BS Spacing	Coverage Area
A	157 dB	1.9 km	3.2 km	9 sq-km
	163 dB	**2.5 km**	**4.3 km**	**16 sq-km**
	170 dB	3.3 km	5.8 km	29 sq-km
B	157 dB	2.6 km	4.5 km	17 sq-km
	163 dB	**3.5 km**	**6.1 km**	**33 sq-km**
	170 dB	4.9 km	8.4 km	61 sq-km
C	157 dB	3.7 km	6.4 km	36 sq-km
	163 dB	**5.2 km**	**9.0 km**	**70 sq-km**
	170 dB	7.3 km	12.6 km	137 sq-km

Table 6: Range and Coverage Area for Typical WiMAX Deployment

Figures 12 and 13 with table 6 should prove useful for estimating the number of base stations and channels per base station required for WiMAX deployments with indoor and outdoor customer terminals.

Other Cost Factors for Terminals

For CAPEX comparisons, all of the previous examples assume the service provider bears the entire cost (equipment plus installation) of the end-user terminals or CPEs. Although this is certainly one alternative it is not the only alternative for dealing with CPE costs. Some other alternatives are:

- Operator provides the CPE and charges the customer a monthly equipment rental fee: Since the rental fee would generally be independent of the terminal type so as not to penalize the end-customers that are further away from the base station, this alternative also favors the use of indoor terminals since the fixed monthly rental fee would recover the CPE cost more quickly

- Customer can opt to purchase their own terminal to forego the monthly rental fee: This also favors the indoor terminal since the customer is more likely to purchase the indoor terminal since a) it is less expensive than the outdoor terminal and b) it is more easily transportable if the customer moves to a new location.

- Operator offers a rebate and makes it higher for the outdoor terminal in order to equalize the price to the end-customer independent of whether the indoor unit or outdoor unit is required. The operator still bears the cost of installation. This approach also favors the deployment of indoor terminals.

Summary and Conclusions

Limiting the base station range in order to support lower cost indoor self-installable customer terminals necessitates a higher investment for base station infrastructure but the terminal savings more than off-sets these costs in a majority of deployment scenarios. In areas with high subscriber densities, generally encountered in urban and many suburban environments, a cost-effective deployment can support 100% indoor CPEs with a significant net savings in CAPEX per subscriber. In the three urban scenarios analyzed, "best case" CAPEX savings based on "average" fixed and variable base station costs ranged from $150 to $210 per subscriber. The following table summarizes the three urban scenarios.

CAPEX Savings per Subscriber for $250 Terminal Price Differential for Three Urban Scenarios					
Scenario	Coverage Area	Subscriber Density	CAPEX Savings/ Subscriber	BS Infrastructure	% Indoor Terminals
1	Urban: 60 sq-km	250/sq-km	High: $177 **Avg.: $150** Low: $123	30 Four-Channel Base Stations	100%
2		375/sq-km	High: $184 **Avg.: $177** Low: $169	30 Six-Channel Base Stations	100%
3		600/sq-km	High: $217 **Avg.: $210** Low: $203		100%

Table 7: Summary for Three Urban Deployment Scenarios

In less populated areas with lower subscriber densities, limiting the range sufficiently to support a high percentage of indoor CPEs will not always be the most cost-effective approach. In the rural scenario analyzed, with a $300 CPE price differential, there is a greater dependence on the relative base station costs. If variable base station costs dominate the infrastructure cost a deployment that supports 100% indoor CPEs will be the more cost-effective deployment alternative, however, if fixed costs dominate, a mixed indoor/outdoor deployment will be the more cost-effective approach.

CAPEX Savings per Subscriber for $300 Terminal Price Differential for Rural Scenario						
Scenario	Coverage Area	Subscriber Density	BS CAPEX	CAPEX Savings/ Subscriber	BS Infrastructure	% Indoor Terminals
4	Rural: 60 sq-km	50/sq-km	Low Fxd, High Var	$165	12 Three-Channel Base Stations	100%
			Avg.	$98		
			High Fxd Low Var	$52	4 Three-Channel Base Stations	27%

Table 9: Summary for Rural Deployment Scenario

It should also be noted that when deploying to support a specific percentage of indoor terminals, the deployment strategy translates from a capacity limited one to a range limited one. This results in excess capacity over and above what is required to provide "minimal" services to a projected market penetration. This capacity is available to the operator for enhanced services to generate additional revenue.