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COST-EFFICIENT WIMAX NETWORK DEPLOYMENT: THE HYBRID OUTDOOR / INDOOR DUAL-LAYER COVERAGE APPROACH

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ABSTRACT

The process of WIMAX radio network design and deployment is greatly affected by the nature of the customer premises equipment and the intended access service, which may be fixed, nomadic or indoor. This paper advances network design methodologies, traditionally used for fixed access, in the scope of hybrid fixed outdoor / indoor-nomadic networks.

With the main objective being performance, time-to-market and cost optimisation, a *dual layer outdoor / indoor coverage* deployment is proposed which allows for co-existence and performance balancing of different customer profiles. By comparing to purely outdoor or indoor deployments, this approach provides benefits, both in terms of equipment reduction and spectrum usage and optimises the deployment costs, especially in the initial phases of the network. This approach is applicable both for OFDM and future OFDMA systems.

I. INTRODUCTION

Different customer premises equipment (i.e. terminal) profiles are commercially developed to satisfy the requirements of fixed (outdoor), nomadic or indoor users. In the first case, a rooftop terminal installation can achieve more favourite propagation conditions and hence can provide higher data rates and link availability. Such terminal profile and deployment choice is highly suitable for business users that can afford the increased equipment and installation costs but most importantly will create higher revenue by purchasing higher bandwidth and QoS services. When targeting mass market penetration of residential users the indoor/nomadic terminals are more suitable, since as a plug and play device it can be purchased more easily and at lower cost, [1]-[2].

Throughout the development of the business plan and network design, the choice of the terminal profile (hence deployment option) is a major issue, as outdoor and indoor terminals have diverse characteristics and require a different design approach. As an example, outdoor terminals have highly directional antennas that can increase the system range but also allow for a more tight frequency re-use. On the other hand, indoor terminals have omni-directional antennas that are not efficient in handling interference conditions, and furthermore the penetration loss can significantly reduce the effective propagation distance. This performance mismatch underpins the complexity of utilizing both terminal profiles in the same network, while it poses several questions on how the proper frequency re-use can be selected or how the interference levels will affect each terminal profile. On the other hand, a hybrid outdoor / indoor deployment appears as the middle, efficient solution between the purely outdoor or purely indoor deployments, both for coverage-limited or capacity-limited environments. This paper proposes a *Hybrid Outdoor / Indoor Dual-Layer Coverage* approach where each terminal profile is deployed in a specific layer. The coverage layers can be distinct (supplementary) or overlap, and the general concept is that to balance the performance mismatch between the terminal profiles, the indoor coverage layer can be selected as a fraction of the outdoor coverage layer.

A very important factor in balancing the interference effects on different terminal profiles is the selection of the channel assignment scheme, since polarization cannot be used for indoor terminals. For different types of networks, several schemes have been proposed in the literature, [4]-[8], where it can be seen that a differentiated performance should be expected when the terminal antenna is directional or omnidirectional, as in fixed or mobile access respectively. Recently, there has been significant interest in Rotated-Interleaved Channel Assignment (RICA), as the most efficient scheme for fixed access, [4]-[6], and in Interleaved Channel assignment (equivalent of MICA, [4]), [7], [8]. A scheme suitable for a hybrid network has not been proposed yet.

In the general context of WIMAX network design, it is required that the existing deployment methodologies are thoroughly analysed in order to set the discussion basis prior to presenting in detail the concept of dual-layer coverage. This analysis involves extensive simulations and comparative interference scenarios considering all terminal profiles and several frequency- re-use factors. Considering that such comparison is not available in the literature, the obtained results are also interesting apart from being a discussion basis. In this paper, the purely outdoor and indoor deployments are compared in terms of radio coverage performance and frequency re-use / interference / capacity performance in sections II and III respectively. The hybrid outdoor / indoor dual-layer coverage concept is presented and discussed in section IV, while in section V the conclusions will form the basis for extensive consideration among manufacturers and operators concerning the deployment of WIMAX networks.

II. RANGE - COVERAGE ANALYSIS

In terms of range and hence radio coverage, the performance difference between outdoor and indoor/nomadic terminals is dependent on two main points: the equipment specs

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(i.e. antenna gain, transmit power) and the propagation conditions (higher path loss, penetration loss). The transmit power for outdoor and indoor terminals can be considered identical, however for nomadic terminals the power consumption and battery life dictate lower transmit power. Additionally the use of omni-directional antennas in indoor and portable devices results in reduced gain compared to the directional outdoor antenna, which may be up to 10 dB. Moreover, the physical location of indoor and nomadic terminals which may even be at street level, hence at much lower height compared to the rooftop, means that the propagation channel will experience higher path loss and shadowing. Furthermore, there are also penetration losses, which may go up to 12 dB for the 2.5 GHz and 15 dB for the 3.5 GHz bands. An initial analysis on the impact of the above differentiations on the system range can be performed by simulating the path loss equations of Stanford University Interim SUI channels models, [10], developed in the scope of IEEE 802.16 working group and are also adopted in relevant WIMAX forum papers. The *indicative* maximum cell range, according to terminal profile (and hence deployment strategy: fixed, indoor) can be estimated from equipment specifications and by using (1).

$$SNR_i = \frac{P_i G_i L_i}{N_i} \qquad (1)$$

where, SNR_i denotes the Signal-to-Noise ratio for link i, P_i is the transmitter power, G_i is the combined BS-terminal antenna gain, L_i is the overall path *loss* and N_i is the receiver sensitivity. By comparing the resulting SNR for each scenario with the threshold for the minimum modulation and coding scheme BPSK-½, SNR_m = 6.4 dB, [9], the cell range can be seen in Figure 1. This range is indicative since the 90% negative shadowing value is considered for the most remote terminal, which may not be the case in practice. The air-interface parameters used in the simulations throughout this paper are outlined in Table 1.

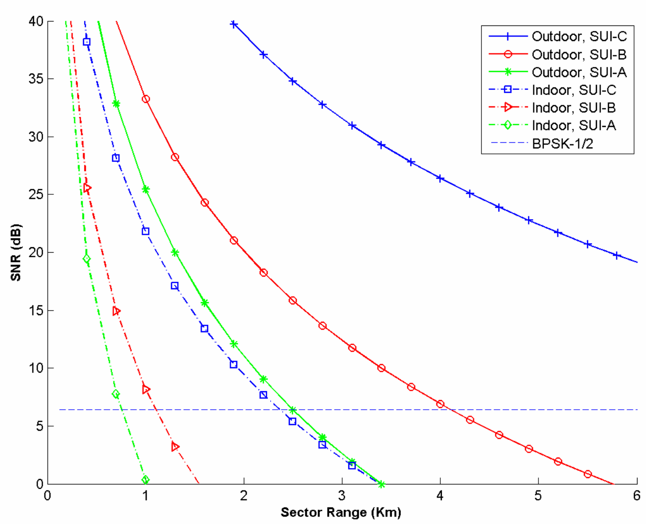

Figure 1: Indicative Maximum Sector Range (Km) for Different Deployment Scenarios and Channel Models.

A careful observation of the crossing point between the SNR_m and the SNR graphs will show that for the same channel model, i.e. SUI-B, the outdoor terminal can operate with approximately 4 times higher system range compared to the indoor. For more relaxed propagation conditions, i.e. SUI-C or even LOS, the discrepancy increases significantly, while for SUI-A it is slightly reduced. The sector range between indoor and nomadic access is not expected to be significantly different, although there is no penetration loss, due to the lower transmit power.

Table 1: Simulation Air-Interface Parameters.

Parameter	Value
Tx Power	23 dBm
BS Antenna Gain	15 dBi (90^0)
Terminal Gain: Fixed, Indoor	16.5 (60^0), 10 dBi
Gain Reduction Factor (Fixed)	1.5 dB
Penetration Loss (Indoor)	15 dB
Receiver Sensitivity	-103 dBm
BS Antenna Height	30m
Terminal Height: Fixed, Indoor	8m, 4m
Frequency Band	3.5 GHz
Channel Bandwidth	3.5 MHz
Service Area Coverage Objective	90%

The difference in the system range affects the achieved radio coverage for outdoor and indoor deployment scenarios and accordingly has a strong impact on the dimensioning, resulting in much higher equipment requirement (BS) for the latter scenario. Considering either hexagonal or square cell shape, the radio coverage area can be approximated by geometry and the well-known circle area equation: πr^2. It can be seen that the achievable coverage area between the two scenarios is dependent on the sector range r. It can be identified that to achieve blanket coverage for a specific service area, the additional required indoor equipment equals to the square of the range difference r_d^2, hence 12 times more in the SUI-B case. It should be noted that this is valid when coverage-limited deployments are considered, where the cell should operate with maximum range. For intermediate cases, the mismatch reduces, until it is eliminated for capacity-limited cases, where the cell operating range drops below the maximum indoor range. The latter case is rather unusual for initial deployments, which are 90% coverage-limited and is more common as the network evolves. The critical point, during network design, is whether to select an outdoor deployment to reduce initial investment or to go directly for indoor to speed up the market penetration. In this case the option of hybrid outdoor / indoor deployment with dual-layer coverage requires an intermediate initial investment, since the cell range can be selected between the outdoor and indoor maximum ranges thus accordingly affecting the BS numbers, while allowing a portion of indoor terminals to be utilized.

In practical deployments, the range mismatch for different terminal profiles may be reduced by adopting sub-channelization, although this is more suitable for rural cases with few customers. This is because sub-channelization may have a strong impact on capacity if utilized widely. A more suitable approach is to attach the indoor terminals adjacent to windows so as to reduce the penetration losses. This method, if widely applied could provide up to 10 dB improvement and could potentially reduce the outdoor/indoor range ratio to 3. This is in favour of the hybrid approach since a higher percentage of indoor terminals will be utilized.

III. INTERFERENCE - CAPACITY ANALYSIS

The most important difference between outdoor and indoor/nomadic terminals is interference handling. Outdoor terminals may utilize highly directional antennas, with 8^0 - 60^0 beamwidth according to propagation conditions, and hence can drastically reject interfering signals with side and back lobe attenuation which may reach up to 35 dB. A narrow antenna may limit the interferers that are received within the main lobe to one or even none. Opposite, indoor and nomadic terminals utilize omni-directional antennas, mainly for orientation issues, which have identical gain both for the signal and interferers. Furthermore, for outdoor terminals the alternative polarization diversity can provide further interference rejection, up to 4-7 dB. Indoor terminals can be operated solely with vertical polarization.

Compared to pre-WIMAX Line-of-Sight (LOS) systems, [6] and WIMAX NLOS systems, [4], [5], which can operate with tight frequency re-use, for nomadic and indoor systems the re-use factor should be more relaxed, similar to that of mobile systems. According to [4], even a re-use factor of F_R = 1 can be applied (a channel is re-used in every cell) in fixed systems and achieve sufficient performance, provided that a careful network planning is adopted. Considering that interference effects are dependent on network deployment geometry, a detailed simulation can provide the exact interference behaviour for different scenarios. The selected performance metric in this case is Signal-to-Interference and Noise Ratio (SINR) which is defined in (2),

$$SINR_i = \frac{S_i}{N_i + \sum I_{j,j\neq i}} \qquad (2)$$

where, S_i is the signal strength, N_i is the receiver sensitivity and I_j is the interfering signal strength. The strength of signal and interferers is estimated according to the nominator of (1). SINR can be reduced to SNR when the interference levels are below the receiver sensitivity level (noise floor), a situation that occurs when the system operates in full range (i.e. rural environments), and/or very relaxed frequency re-use. Accordingly SINR can be approximated by SIR when interference is higher than the receiver sensitivity, a situation that is common in urban deployments where system range is small due to high capacity/area unit requirements. Assuming urban deployment, where SUI-B propagation conditions exist and cell range of 2 Km and 0.6 Km are expected for fixed and indoor scenarios respectively. The sector capacity (Mbps / 3.5 MHz) and interference plus noise levels (I+N) are presented in Table 2 for different re-use factors. The capacity is estimated by mapping the SINR performance of terminals to the spectral efficiency presented in the standard, [9]. The evaluated terminals are located in the center cell of a 49-cell network and receive interference for two layers of co-channel cells. According to [4], the most efficient Rotated-Interleaved Channel Assignment is selected for the all-outdoor deployment, while the Monotonous-Interleaved Channel Assignment (also referred as Interleaved Channel Assignment, [7]-[8]) is selected as the best scheme for all-indoor deployment.

Table 2: Sector Capacity (Mbps / 3.5 MHz) and I+N Levels for Outdoor, Indoor and Nomadic Deployment, SUI-B Channel Model and Different Frequency Re-Use Factors.

SUI 3/4		F_R=1		F_R=2		F_R=3	
		DL	*UL*	*DL*	*UL*	*DL*	*UL*
Fixed Outdoor	**Cap.** (Mbps)	6.98	5.22	7.7	7.07	7.84	7.35
	I+N (dB)	-97.35	-90.13	-100.9	-96.66	-101.2	-97.65
Indoor	**Cap.** (Mbps)	4.14	2.32	5.88	4.29	6.46	4.76
	I+N (dB)	-87.72	-81.17	-94.14	-88.71	-96.87	-91.07
Nomadic	**Cap.** (Mbps)	4.11	2.28	5.99	4.01	6.93	4.97
	I+N (dB)	-72.9	-66.44	-80.11	-73.67	-83.8	-76.31

By observing the impact of frequency re-use on outdoor terminals, it can be seen that a reasonable performance can be achieved with frequency re-use $F_R=1$, while for $F_R=2$ a noticeable improvement appears (~10% *DL*, 34% *UL*). The effect of re-use factor is almost identical for the indoor and nomadic terminals where, for $F_R=1$, performance is unacceptable especially in the uplink. A major improvement appears for more relaxed re-use factors (up to 56% *DL*, 100% *UL*). The corresponding I+N levels in the various cases clearly show the impact of using omni-directional antennas. In addition to the previous range mismatch, according to Table 2 it can be concluded that for indoor and nomadic terminals at least double the spectrum is required, not to mention that the sector capacity performance is still inferior to that of outdoor terminals. Hence not only higher spectrum acquisition costs should be accounted for but also more equipment if the deployment is capacity limited. Indicatively, assuming that the main deployment objective is capacity (which determines the cell range, hence ranges below 1 Km), considering that outdoor terminals will operate with double channel bandwidth, the required indoor equipment would be more than two-fold. It should be mentioned that in cases where operators have limited spectrum, the aggressive $F_R=1$ for outdoor deployment may be the only viable option. In these cases, the hybrid outdoor / indoor dual-layer deployment approach could actually operate with the same re-use factor as the all-outdoor case and accommodate a portion of indoor terminals while not incurring in more equipment or spectrum costs.

IV. HYBRID OUTDOOR/INDOOR NETWORK WITH FRACTIONAL-LAYERED COVERAGE

A hybrid network is proposed in this section, where both outdoor and indoor terminals are accommodated. The scope is to achieve low BS and spectrum requirements, as in outdoor deployment, while incorporating the cheaper and with zero-installation cost indoor terminals. Therefore the challenge is to replace a portion of outdoor terminals with indoor while balancing their performance within the sector. Consider a deployment scenario where the cell/sector range is selected considering the performance of the outdoor terminals, i.e. 3 km for SUI-B. However, up to 1 Km, indoor terminals are utilized instead of outdoor. This hybrid network is based on the concept of dual-layer coverage, where the indoor coverage layer (where potentially an indoor terminal can be deployed) is a fraction of the outdoor coverage, as it can be seen in Figure 2.

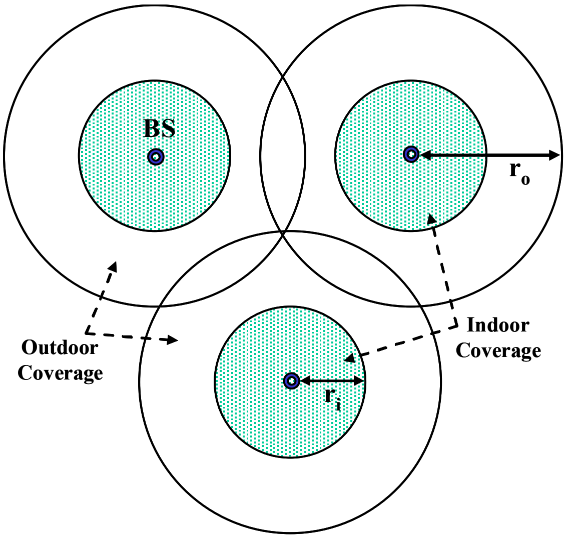

Figure 2: Hybrid Outdoor / Indoor Dual Layer Coverage.

By selecting the range of indoor network, r_i in Figure 2, as a fraction of the range of the outdoor, r_o, there are two achievements: first the link gain budget of the indoor terminal comes in balance with the outdoor (for their respective ranges), and second by improving the signal strength the SINR performance of indoor terminals is also improved. Observe (3), an analytical form of (2), where the interfering components are normalized to the signal:

$$SINR_i = \frac{P_i G_i L_i}{N_i + \sum P_j G_j L_j} \Rightarrow$$

$$SINR_i = \sum\left(\frac{P_j}{P_i}\frac{G_j}{G_i}\frac{L_j}{L_i} + \frac{N_i}{P_i G_i L_i}\right)^{-1} \qquad (3)$$

Assuming that the transmit powers are equal, the SINR depends on the normalized antenna gain and the path loss terms. In outdoor terminals, due to directional antennas the corresponding term takes values much lower than unity, opposite of what applies in indoor terminals where $G_i \approx G_i$. In the latter case, by selecting $r_i < r_o$, L_i may considerably be increased thus accordingly reducing the path loss term. Consequently the performance difference, indicated in the previous sections is now improved. Essentially, the dual-layer coverage provides a percentage of indoor terminals which is equivalent to the fraction Δ^2, with $\Delta = r_i / r_o$.

It is apparent that such hybrid configuration poses questions on how the system will behave in terms of interference and according to the re-use factor. Considering solely the indoor layer performance, due to the reduced signal propagation distance, and hence increased signal strength, the system can operate even with $F_R=1$, which is superior than the all-indoor performance (refer to Table 2). In contrast, the outdoor performance is reduced since only the remote terminals, in the non-overlapping coverage disk, which achieve lower spectral efficiency, are now accounted for.

The hybrid sector capacity is derived by weighting the individual indoor layer and outdoor layer capacity with the fraction of the corresponding service coverage percentage and is presented in Figure 3. The first observation is that as the sector range increases the capacity decreases and this is mainly due to the indoor layer performance where terminals start to appear close or even beyond maximum indoor system range (refer to Figure 1). Furthermore, for higher values of Δ the performance reduces due to the increasing interference levels, which approach that of all-indoor scenario with $F_R=1$. By selecting a specific sector deployment range, a sensible Δ and hence r_i can be selected. For target DL capacity of around 5.8 Mbps (upper limit for 64QAM-¾ is 9 Mbps) and a sector range of $r_o = 2$ Km, it can be observed that $\Delta = 0.5$ and hence a 25% of indoor terminals should be considered at $r_i = 1$ Km.

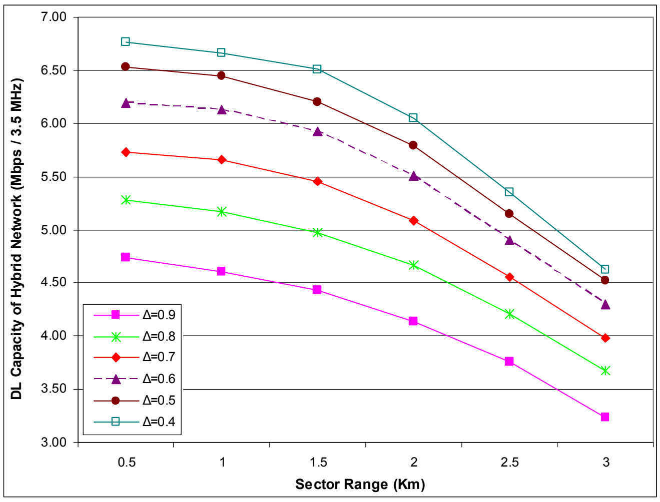

Figure 3: DL Capacity of Hybrid Network (Mbps / 3.5 MHz) vs. Sector Range (Km) and for Different Fractions for Indoor Coverage (Δ, $\Delta=r_i/r_o$).

Figure 3 allows the network designer to decide between the percentage of indoor terminals and hybrid capacity target that suits the design objectives. It should be mentioned that if the equipment specs are improved in the future, the hybrid performance in Figure 3 will be shifted right along the x-axis, indicating that for a particular *Δ* a higher sector range will be achieved, a useful outcome for coverage limited deployments.

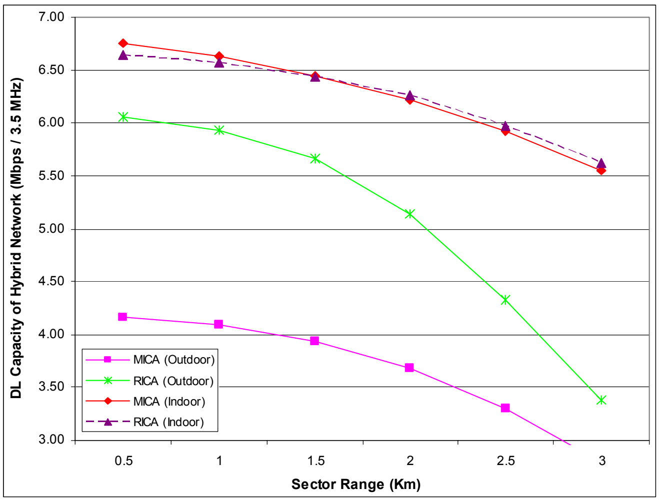

Figure 4: DL Capacity of Hybrid Network (Mbps / 3.5 MHz) vs. Sector Range (Km), comparing RICA and MICA schemes for *Δ=0.6*.

The performance in Figure 3 is derived by selecting RICA as the channel assignment scheme. Extensive simulations showed that RICA is the most efficient choice for hybrid deployment, being much superior to MICA. Actually, for the indoor layer both schemes are identically efficient, as it can be observed in Figure 4, however for the outdoor RICA is considerably more efficient, leveraging the hybrid performance. Especially for close sector ranges, RICA is up to 50% more efficient than MICA. For uplink performance, results for channel assignment schemes in Figure 4 and the hybrid capacity for different *Δ* values in Figure 3 are similar, hence are not presented.

The exact gains from adopting the hybrid fractional-layered outdoor/indoor coverage depend on the deployment strategy. In coverage-limited scenarios the increased cost-efficiency comes from the reduced BS and spectrum requirements that a hybrid deployment can achieve compared to the purely indoor case. Due to the high cell ranges, the percentage of indoor terminals is still small, which facilitates a quick deployment. When it comes to capacity-limited deployments, the number of BS is similar between all deployment approaches; still the hybrid deployment can operate with more tight frequency reuse and a significant number of indoor terminals. Finally, an advantage of the hybrid deployment is that it facilitates a more straight-forward transition to all-indoor networks that are expected to dominate in the future due to Mobile WIMAX standard. It is in the discretion of the wireless network design engineer to exploit in the best possible way the gain of hybrid deployment, by carefully selecting the trade-off capacity vs. percentage of indoor terminals according to the operator's business plan and deployment strategy.

V. CONCLUSIONS

A development to traditional deployment scenarios, which can be either purely outdoor or purely indoor coverage, is presented in this paper. The concept of combining both terminal profiles in a *Hybrid Outdoor / Indoor Dual-Layer Coverage* provides several advantages, with the most important being the flexibility to address in a cost-efficient way the network deployment. Either in coverage-limited scenarios or in capacity-limited scenarios the reduction in equipment and spectrum requirements are visible, while the adoption of plug and play indoor terminals can boost the market penetration. Results in this paper can be used as guidelines for network design engineers to select the proper range per coverage layer in order to achieve a specific hybrid capacity per frequency channel. Furthermore, the most appropriate channel assignment scheme is proposed so that interference is mitigated and robust system operation can be achieved. Future work can be focused on the technoeconomical aspects of this method, and how these can be exploited in real-life scenarios.

VI. ACKNOWLEDGEMENTS

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