ABSTRACT

Traditionally, mobile operators have planned their networks to accommodate mobile terminals at ground level. Increasingly, mobile users communicate while stationary from within high-rise buildings. With mobiles operating at a variety of different heights and mobilities, plus the requirement to accommodate increasing teletraffic and multimedia services, there is a need to compact small cells into the three-dimensional city space. This article is concerned with using city buildings to act as electromagnetic molds that define the size and shape of each three-dimensional cell. Issues related to using these cells to form a mobile radio network are discussed.

Small Cell City

Shirin Dehghan and Raymond Steele, Multiple Access Communications Ltd.

To provide multimedia services to people who may be essentially anywhere, moving at any speed, is a daunting task. These are the aims of the Universal Mobile Telecommunications System (UMTS) and the International Telecommunications Union's (ITU's) IMT2000 system (for International Mobile Telecommunications by the year 2000) [1, 2]. UMTS and IMT2000 are likely to melt down into one international global mobile telecommunications network and be deployed early in the next century. To realize UMTS the regulators have allocated 220 MHz of spectrum in the 1.885–2.200 GHz frequency band. Because some services will require a data rate of 2 Mb/s, and many millions of subscribers are expected, it is evident that spectral efficiencies some orders of magnitude higher than second-generation cellular systems must be achieved. While wire systems can increase capacity by the simple expedient of laying another cable or optical fiber, in the mobile radio environment the equivalent is to improve the frequency reuse factor, that is, to reuse the allotted spectrum over a geographical area more often.

In the startup phase of a mobile network capacity is not an issue, and radio coverage is either rolled out from some major conurbation or built up from key areas over a state or country. While coverage in rural areas is incomplete, capacity problems begin to surface in urban areas and are dealt with by improving the frequency reuse by a number of strategies. These include using cell splitting, base stations (BSs) employing sectorized antennas with downtilt (if required), underlay-overlay procedures, and the deployment of additional BSs. Although the introduction of additional BSs results in smaller cells, the BS antennas still tend to be located on top of tall buildings in urban centers. Eventually the operator is forced to abandon the concept of a single layer of cells, albeit of varying size, being as small as 500 m and becoming progressively larger the further they are located from the city center. The operator now needs to use the city itself to act as electromagnetic molds for a complex multilayering of cells, with the smallest cells as the bottom tier and the largest cells as the top tier.

Early cellular radio networks were created for mobile users in cars, and consequently radio coverage was concentrated in streets. This is interesting because right from the inception of mobile radio many visitors to buildings used their mobile telephones there. Cordless telephones (CTs) such as CT2, Digital European CT (DECT), and Personal Handyphone System (PHS) are now available [3], and can be operated as wireless private access branch exchanges (PABXs) where the subscribers only pay the public switched telephone network/integrated services digital network (PSTN/ISDN) operators. When used for telepoint services, the subscribers pay the telepoint operators, who in turn are charged for the use of the PSTN/ISDN. Cellular operators would like to capture the telepoint and wireless PABX services, but to do this they need to operate in the same street microcells and office microcells as do CTs. This requires cellular operators to have small inexpensive cellular equipment, and this is coming onto the market. Cellular operators must now consider planning indoor microcells, often referred to as *picocells*; street microcells; oversailing minicells that, when small, are three-dimensional microcells providing signal penetration into buildings and, when large, may overlay many street microcells; and sectors of macrocells, formed using antennas located on top of the tallest buildings, which overlay minicells and microcells. These different layers of cells are interactive, since a mobile must be able to be handed over between them. At the same time, great care must be exercised in minimizing co-channel interference. This is far from easy because the cell shapes are determined by the shapes and positions of buildings, building construction and content, foliage, terrain, and a myriad of second-order effects.

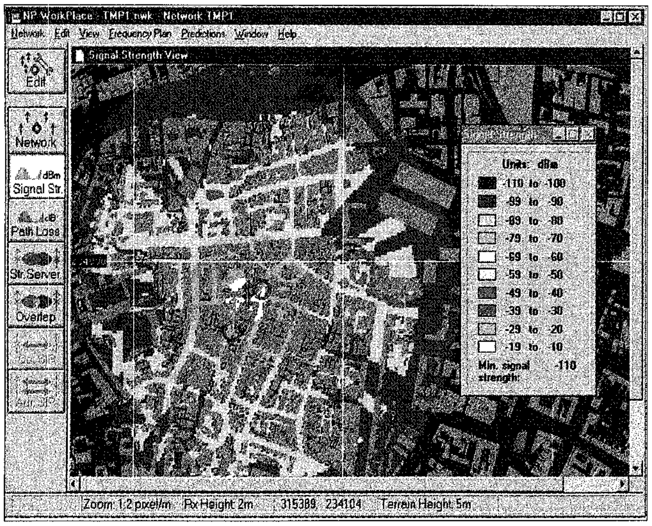
In this discourse we will address some of the issues relating to the planning of small cells in city centers. Street microcells, minicells, and indoor picocells will be discussed. We will concentrate on the radio prediction aspects.

TYPES OF OUTDOOR CELLS IN CITIES

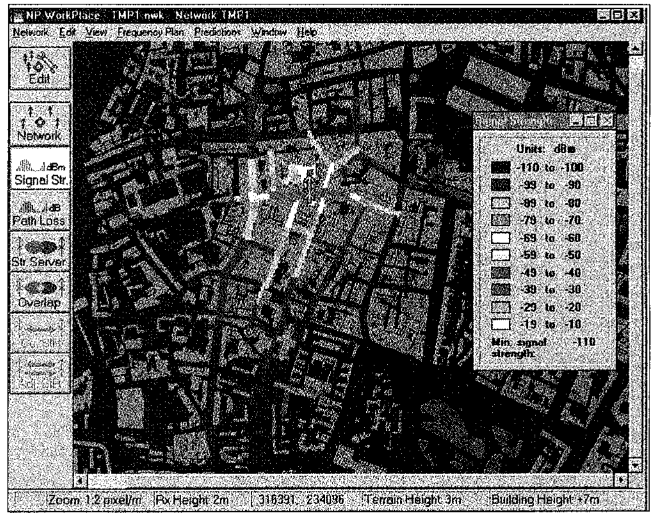
The smaller the cell, the more subscribers per unit area, or the higher the bit rates of services that can be supported [4]. Small cells can be implemented using small-sized BS equipment. The transmitter power is low to keep the dimensions of the cell small; the large antennas associated with macrocells are replaced with small antennas; and for outdoor cells the sites are on top of smaller buildings or on the walls of buildings. The small size of the equipment makes it easy to install. The site acquisition costs are lower and the planning permission easier to obtain than for macrocellular sites. The backhaul network may be the major cost, since it may involve the installation of an optical fiber local area network (LAN), or a wireless LAN operating at a different, usually higher, propagation frequency.

As the network matures, the radio planner will observe that

0163-6804/97/$10.00 © 1997 IEEE



■ **Figure 1.** *Clutter-based algorithm prediction of a microcell with BS antenna at 6 m.*



■ **Figure 2.** *Microcellular prediction using NP WorkPlace with BS as sited in Fig. 1.*

some of the sectors are being overloaded, in spite of numerous replanning attempts. At this point it is evident that microcells and minicells should be introduced. If the operator is bold, clusters of these cells may be located within the overloaded macrocellular sector. This will certainly result in excessive capacity or, from the user's point of view, the provision of a very low blocking probability on the radio network. If the operator is timid (or wise, depending on your point of view), teletraffic sniffers will be employed to identify hot spots within the sector. Microcellular and minicellular BS locations will now be identified and tailored to the teletraffic demand. Sometimes the network planners are told by management to plan for a large demand in teletraffic in certain areas. The number of BSs required to meet this demand is calculated and their location determined with the aid of radio planning tools [5, 6].

In city centers street microcells are formed with microcellular BS antennas at some 6–9 m above street level. They can be mounted on lampposts or on the outside walls of buildings. These street microcells may be viewed as two-dimensional in that they are primarily designed for mobiles in the streets, although coverage will be provided for some offices at the ground level and on higher floors. By raising the antenna height we form minicells (i.e., cells larger than microcells), provided the BS transmitting power is increased. However, if the transmitted power is restrained to be similar to the microcellular power, we have three-dimensional microcells. We therefore have the following classification of city street cells: 2D microcells, 3D microcells, minicells that overlay a number of microcells, and macrocells that overlay a number of minicells. The macrocells will be discarded in city centers as teletraffic demand increases, and the biggest cells will be oversailing minicells of dimensions 1–2 km.

Planning Tools for Small City Cells

Planning tools need to be able to predict the coverage of minicells and 2D and 3D microcells in the center of cities where the buildings are of varying height, cross-sectional area, and shape, sited in irregular positions, and cohabit with parks, lakes, and rivers. Some operators introducing small cells into city centers remain irrationally faithful to their existing macrocellular planning tools. These tools use terrain databases and clutter information in clutter-based models. These tools were conceived for planning the coverage of cells having dimensions of 5 to 60 km, and originally had large bin sizes of 250 m x 250 m. Although they have been continuously refined to predict cells of some 0.5 km, their bin sizes rarely go below 50 m x 50 m, which means that they cannot, and do not, take into consideration individual buildings. Hence, they view buildings as clutter of a type depending on building density and average building height per bin. To designers of small cell planning tools, the word clutter is anathema when used in connection with building data. Small cells are created by the city, whose shapes they reflect. A 2D microcell is the shape of a set of contiguous streets; if the streets are irregular, so is the 2D microcell. The planner must skillfully use the city to create the multilayering of cells required; therefore, the planning tools must utilize 3D maps of cities that enable bin sizes of only 5 m x 5 m to be employed. In a dense urban environment the operator wants to know the potential problems in particular streets and individual buildings. Thus, such a high resolution is essential for planning in this type of environment.

Let us now consider an example of predicting the received signal strength contours for an arbitrarily placed microcellular BS. Figure 1 shows a plan of a city center, where the buildings are in dark gray while the black areas show roads, open spaces, parks, and a river. The colors represent the path loss changes at ground level between the buildings. This plot is provided using a clutter-based tool where the microcellular BS dipole antenna height is 6 m. If we make the same prediction using algorithms specifically tailored for individual buildings and foliage, we obtain the coverage plot[1] shown in Fig. 2. Observe that the predictions are significantly different, particularly in the vicinity of the cell site, and also much more accurate than those obtained by the clutter-based prediction algorithm. When the BS is moved a few tens of meters around the corner of the building, the microcellular prediction changes to the plot shown in Fig. 3. Notice that this small change in BS position has caused a dramatic change in the coverage. However, the clutter-based prediction plot is only marginally changed from that shown in Fig. 1. In other words, the profound and subtle changes in coverage that actually occur due to the presence of individual buildings, and as shown by the microcellular planning tool, are missed completely by the macrocellular clutter-based tool [7].

This example illustrates the necessity of employing algorithms that utilize the position, cross-sectional areas, and heights of buildings in order to provide a sufficiently accurate prediction of signal strength along the different streets. Armed with these predictions, and those of neighboring

[1] *These plots were produced using the proprietary Network Planner WorkPlace tool from Multiple Access Communications Ltd.*

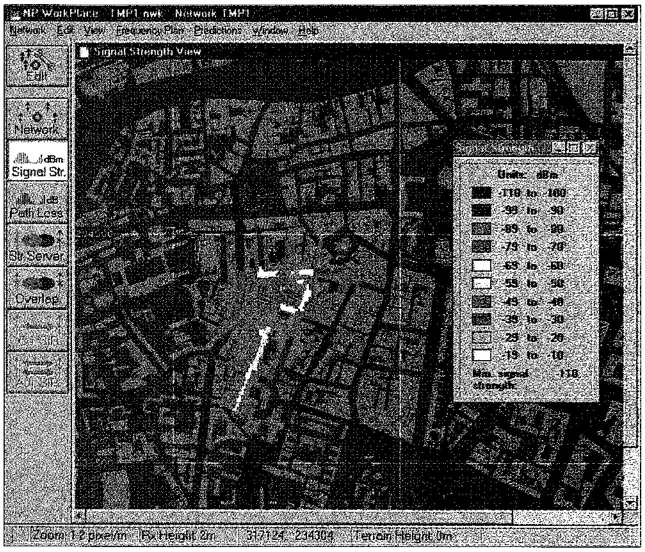


Figure 3. *Microcellular prediction using NP WorkPlace when the BS in Fig. 2 is moved around the corner.*

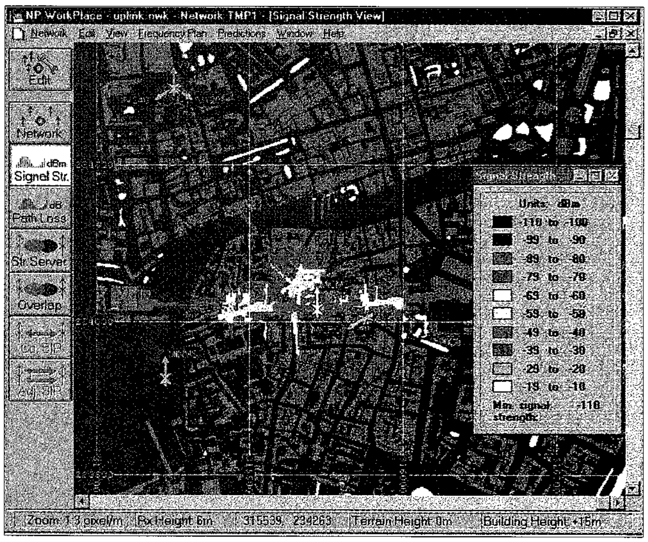


Figure 4. *Signal strength profile at 6 m above ground level, from an MS in a microcell.*

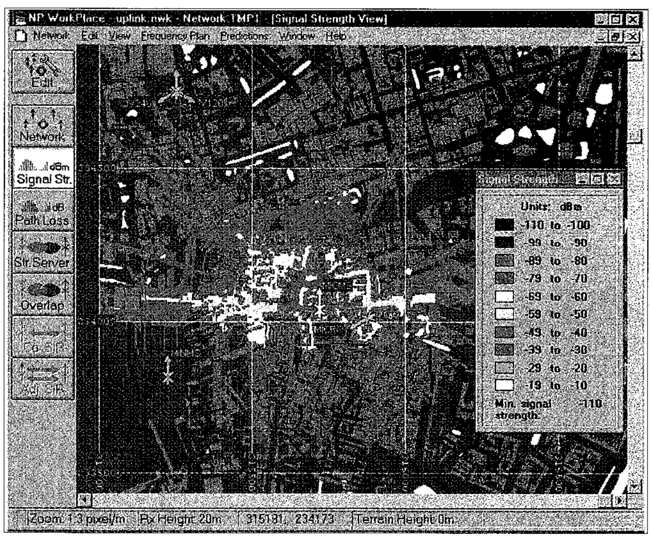


Figure 5. *Signal strength profiles at 2 m above ground level, from an MS in a microcell.*

microcells, other system parameters, such as strongest server in an area, signal-to-co-channel interference ratio, and signal-to-adjacent channel interference ratio, can be computed and displayed.

Introducing Isolated Microcells in a Macrocellular Network

When single microcells are being introduced to relieve teletraffic hot spots, with care it is possible to let the microcell use the same channel sets as the macrocells. Our concern in using this approach is to ensure that the interference generated between microcells and macrocells is acceptable. Because we have small macrocells in dense urban environments, we will refer to them as minicells. Let us commence by considering a single microcell (MICRO) and a single minicell (S1), and discuss in general terms the differences in the uplink (i.e., reverse) transmissions. To simplify matters further we will consider a single mobile station (MS) transmitting to its microcellular BS whose antenna height is, say, 6 m. The transmitted signal experiences losses along the streets, into buildings, and diffraction and reflection around the buildings. The horizontal diffraction over roofs does not significantly affect the coverage from the MS at street level. Figure 4 shows the coverage from an MS. A little to the right and below there is a gray arrow representing the microcellular BS. In communicating with its microcellular BS, the MS in the microcell may interfere with a sectorized minicellular BS, shown by the three gray arrows spaced 120° apart, and located in the top left corner of Fig. 4. We observe that for the plot shown in Fig. 4, which is at a height of 6 m, there is negligible signal at the minicell site. The MS is assumed to be transmitting at a power of 30 dBm. However, to identify the interference at the minicell BS we must provide a plot at the elevation of the minicell BS antenna, namely 20 m. This coverage plot of the MS in the microcell at a height of 20 m is shown in Fig. 5. The received signal level at the minicell site is –95 dBm. Since the gain of the MS antenna is unity, while the gain of the minicell sectorized BS antenna is 17 dB, the actual interference is more than –95 dBm, a value that may well cause substantial interference. We also note that the MS is not at the edge of its microcell, so in this figure > –95 dBm is not the maximum interference which may occur. The reason the coverage is so much greater by the MS in the microcell at an elevation of 20 m is due to diffraction over the tops of the buildings near the MS, followed by a relatively unimpeded path to the minicell BS site.

Contrast this situation with an MS in the minicell. By the same arguments as above, it is not too difficult for its transmissions to reach the minicellular BS at an elevation of 20 m, and for this particular MS position the MS is powered down to 20 dBm. In order to ascertain whether this MS will interfere with the microcell BS we plot the coverage from the MS at the BS height of 6 m. This plot is shown in Fig. 6. Notice that the MS has a negligible effect on the microcellular BS with its dipole antenna. Indeed, this situation prevails even when the MS transmission power is increased to 40 dBm.

On the downlink it is evident that the interference on the MS in the minicell from the microcellular BS will, in general, be negligible. The MS in the microcell is, however, more prone to interference from the minicellular BS. The weak link, both the uplink and the downlink, is that between the minicellular BS and the microcellular MS, and it is the interference between these two entities that is important in network planning.

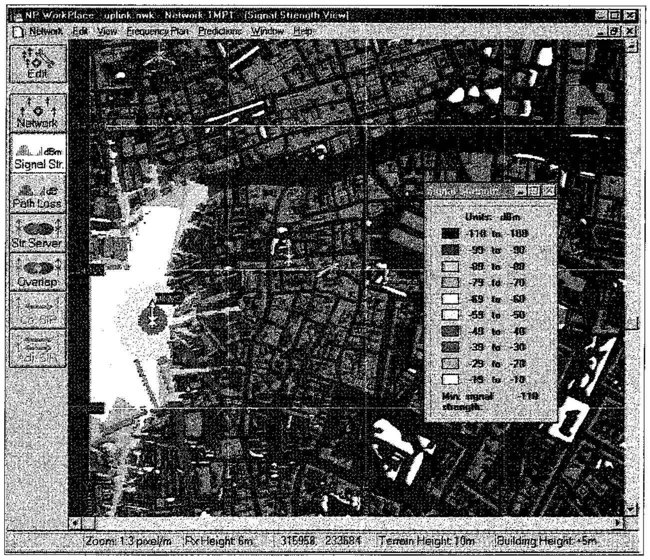
During the planning phase of the minicellular network, the received signal level from each minicell in the area where the microcell is to be located is known. Therefore, the minicell with the lowest received levels in the area where the microcell BS is to be deployed will be co-channelled with the microcell. The total downlink interference, namely the sum of the co-channel and adjacent channel interferences, is determined in the vicinity of the proposed microcell site. Next, the interference of the microcell on the co-channel minicells is predicted. From these sets of predictions the signal-to-interference ratio (SIR) contours of the microcell are identified and the boundary selected as the one where the SIR is above the threshold for the acceptable link quality.

Introducing a single microcell into a macrocellular cluster is difficult and needs considerable care for this case where the microcell does not have a unique channel set. When clusters of microcells need to be deployed, channel set partitioning is vital [4]. If this is not done the network is spectrally inefficient, because it is necessary to deploy large macrocellular clusters in order for both microcells and macrocells to operate with acceptable SIRs.

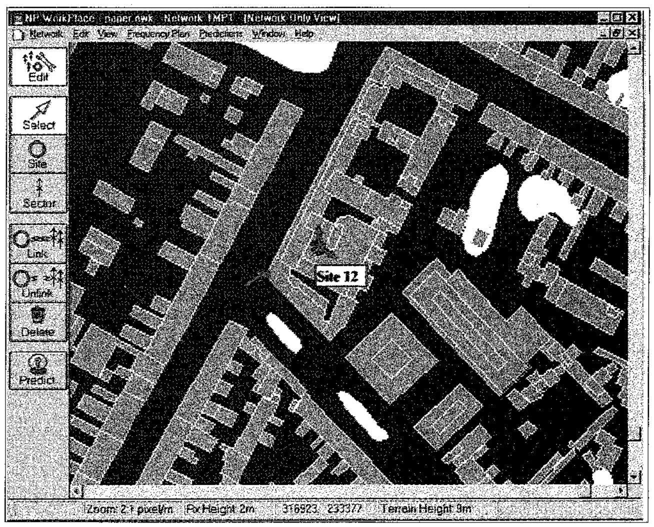
A Minicellular Network of Sites

Placing BSs on the sides of buildings and on the roofs of small buildings enables us to form 3D microcells or minicells, depending on the height of the antenna and the surrounding buildings. We can predict the coverage at different heights, both above and below the height of the BS antenna. Thus, at any height we will know the received signal strength around, say, the sixth floor of a building. Armed with a building penetration loss and a path loss law for the building based on a simple furniture loss factor and the number of walls [8], we can crudely estimate the in-building coverage. On repeating this for all buildings at the same height (which is not necessarily the same floor level due to terrain variations), we can compute the indoor SIR and other key parameters using the planning tool.

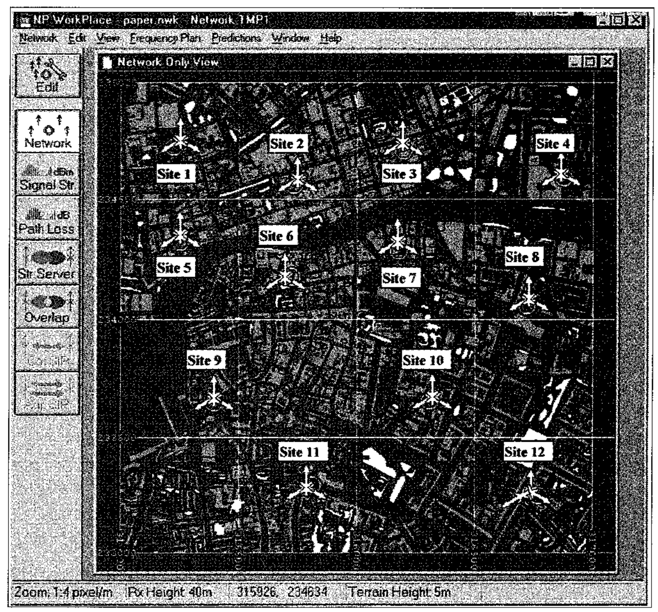
As part of a network, Fig. 7 shows a 2D display of buildings in dark gray, vegetation in white, and open spaces in black. However, sliding the pointer over the screen reveals the height of the black areas relative to sea level and the heights of the buildings, which can change over the cross-sectional area. We are therefore observing a 3D city database. A site consisting of three sectors has been located on a building at an elevation of 25 m with an antenna mast of 4 m. Two of the sectors are placed on the rooftop. The third sector is placed on the side of the building at 15 m above ground level, equivalent to the fourth floor elevation of the building, and is pointing 240° from the north. The rest of the network is arranged in a four-cell frequency reuse with three sectors per cell for mobiles on the street. This network is shown in Fig. 8. All the sites have been placed on buildings of medium height (approximately 20 m tall). The majority of the tall buildings (25–30 m) are concentrated in the southern part of the city, while in the northern areas the buildings are generally 10–25 m tall. Predictions are performed for each sector at MS heights of 1.5 and 40 m above ground level. This has been done to investigate the coverage at street level and the 10th floor of the buildings, respectively, within the 2 km x 2 km area. Figures 9 and 10 display the corresponding received signal strength plots at receiver heights of 1.5 and 40 m, respectively. The coverage predictions are presented in 5-m bins. Observe that for the same transmitter power, the effective cell size is a function of MS height. An MS in an office at a height of 40 m is in a cell that is many times larger than an MS at ground level. This is appropriate because there are likely to be fewer MSs at 40 m than at 1.5 m, since every building will have a ground floor, but only the tallest buildings will have floors at



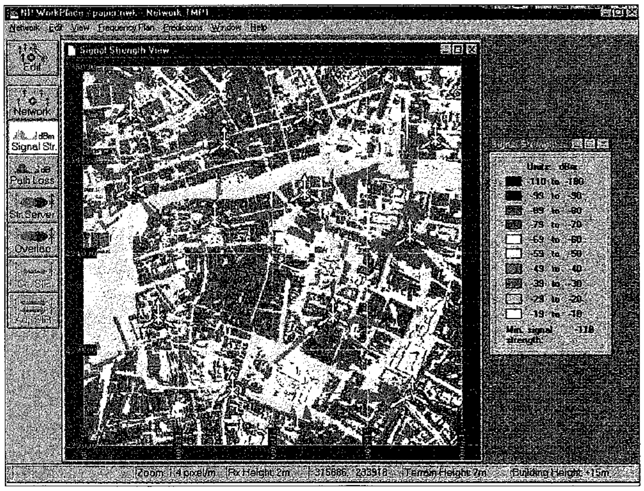
■ **Figure 6.** *Signal strength profiles at 6 m above ground level, from an MS in a minicell.*



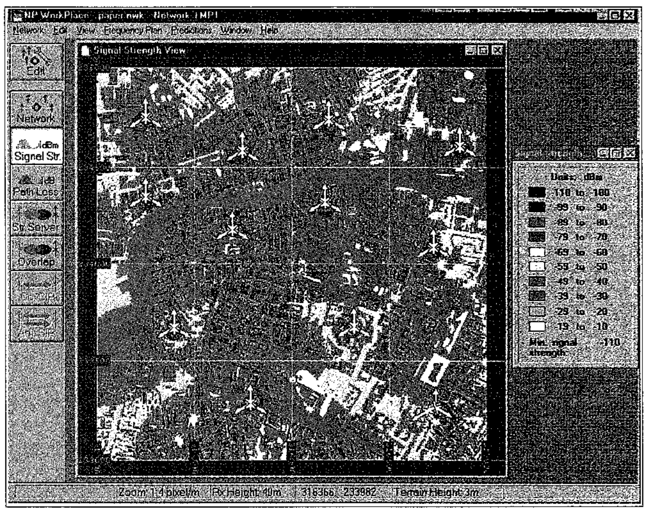
■ **Figure 7.** *Two-dimensional display of buildings.*



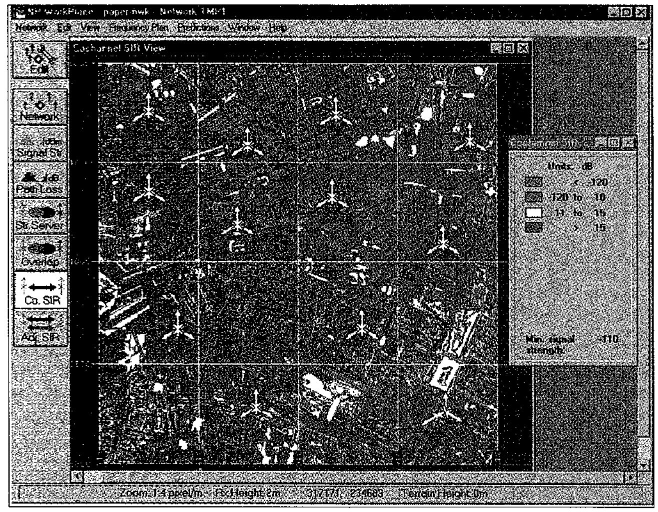
■ **Figure 8.** *Network of minicells arranged to achieve a 3 x 4 repeat pattern for an MS at street level.*



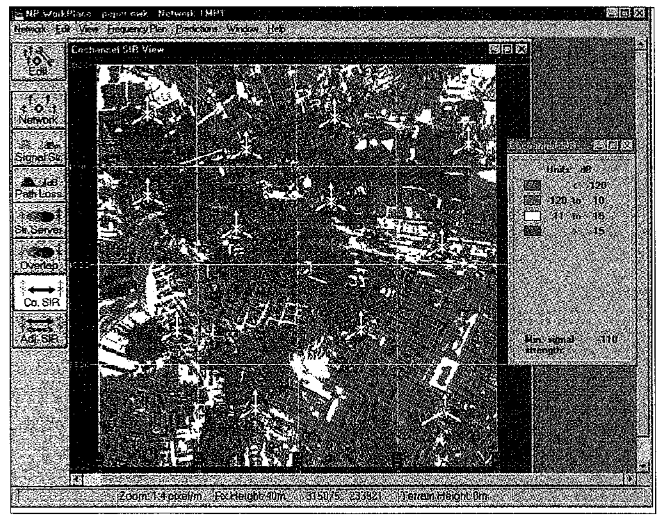
■ **Figure 9.** *Composite signal strength prediction at an MS height of 1.5 m above ground level.*



■ **Figure 10.** *Composite signal strength prediction at an MS height of 40 m above ground level.*



■ **Figure 11.** *Area interference at an MS height of 1.5 m.*



■ **Figure 12.** *Area interference at an MS height of 40 m.*

40 m. We also notice that the shape of the minicell at the lower elevations is irregular and is largely determined by the buildings near the BS site, whereas at the higher elevations there are relatively few buildings to affect the coverage.

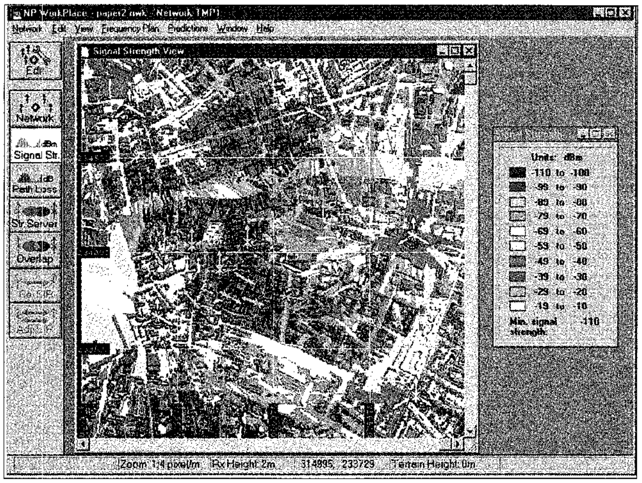
In order to determine the SIR we must have a frequency plan. Table 1 shows frequency groups A, B, C, and D, and how they are assigned to the sectors of the minicellular antennas in Fig. 8. Note that sectors pointing in the same direction on the sites are co-channelled in this four cells per cluster, three sectors per cell arrangement.

The composite co-channel SIRs for the network at MS heights of 1.5 and 40 m above ground level are shown in Figs. 11 and 12, respectively. The sectorized minicells provide reasonable SIR thresholds at street level with sites 9 and 12 suffering from unacceptable interference. This plan is designed to be exemplary rather than optimum. Mobile receivers in tall buildings suffer from intolerable interference levels. However, the network is acceptable if the operator is only interested in providing a high quality service for mobiles at street level. Thus, as the height of the MS is increased, the natural overlays created by the nature of radio propagation reduce the quality of service drastically. The severity of the situation worsens with macrocells as they are generally placed on top of the tallest buildings and have line of sight to many of the surrounding buildings.

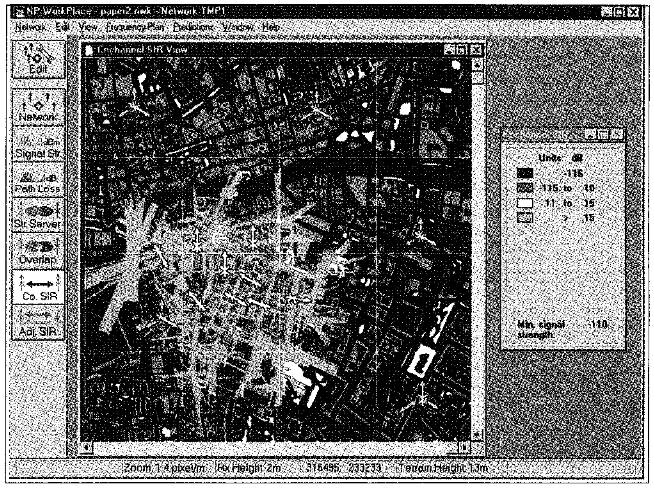
Mixed-Mode Cells and Frequency Partitioning

We have shown that locating a BS at modest elevations such as 20 m may yield acceptable coverage and SIR levels for street mobiles but result in unacceptably high levels of interference in offices in tall buildings (assuming the penetration losses into buildings lies between 10 and 30 dB, depending on building construction). In order to offer a service for street mobiles and office workers, we need to deploy a contiguous set of street microcells and have a limited number of minicells that may assist some street microcells, but are primarily concerned with providing a service for office workers. Design of this two-tier arrangement is simple to achieve if we use channel set partitioning. For a system where one carrier carries multiple channels, the term *frequency partitioning* may be applied [4].

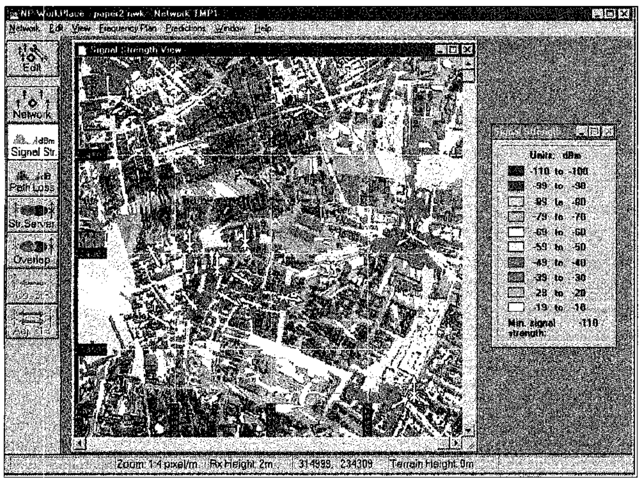
As an example, let us consider a city where an area of it produces a disproportionate amount of teletraffic. This area is identified using teletraffic sniffers. Into this area we deploy a set of nine street microcells. Surrounding these microcells with the antennas at 6 m, are a set of five minicells whose antennas are at approximately 20 m. Figure 13 shows the position of the three sectorized minicell BS antennas and the omnidirectional street microcell BS antennas. The plot relates



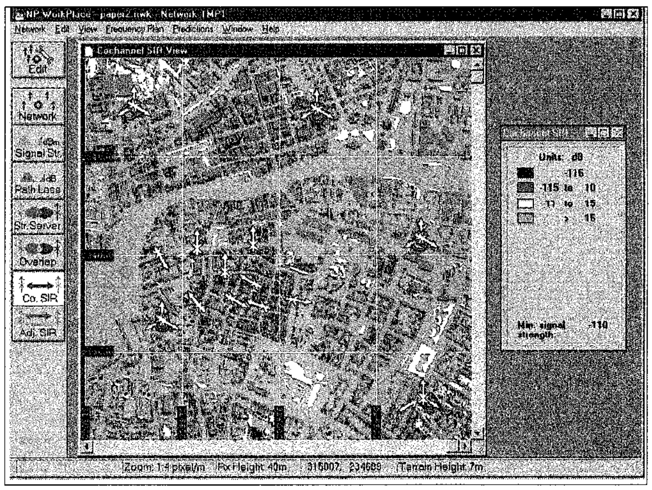
■ **Figure 13.** *Received signal levels at 2 m due to five minicell BSs.*



■ **Figure 15.** *SIR plots at 2 m for the microcells.*



■ **Figure 14.** *Received signal levels at 2 m when both the minicell and microcell layers are active.*



■ **Figure 16.** *SIR plots at 40 m for the minicells.*

to the received signal levels provided only by minicells labeled 9, 1, 3, 8, and 12 in Fig. 8 in an area 2 km x 2 km. The other minicell sites have been removed. When the microcells are turned on, the minimum received signal levels are those shown in Fig. 14. Most of the 2 km x 2 km area of the city has acceptable received signal levels. To increase the coverage and capacity, more microcells may be deployed.

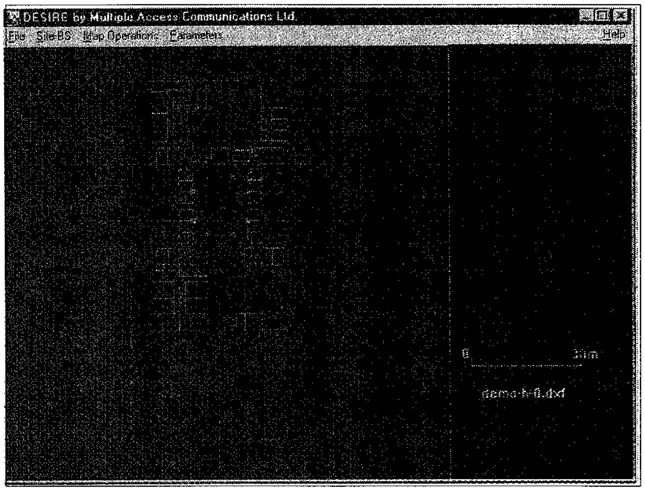
Frequency groups	Co-channel sectors on sites
A	1, 3, 9, and 11
B	2, 4, 10, and 12
C	5 and 7
D	6 and 8

■ **Table 1.** *Frequency assignment used for the network of Fig. 8.*

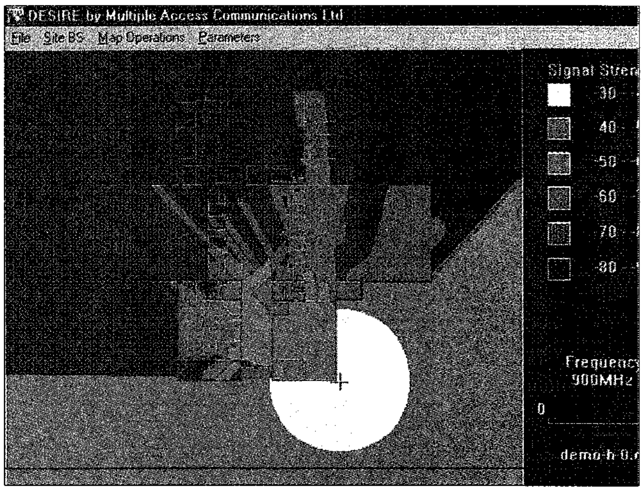
Deploying a four-cell reuse plan for the microcells, and utilizing the frequency plan shown in Table 1 for the minicells, we obtain satisfactory SIR plots for the street microcells and for the minicells at 40 m, shown in Figs. 15 and 16, respectively. The SIR plot for minicells at lower elevations (not shown) is better than the one at 40 m, and remember that the microcells and minicells cannot be co-channelled because different channel sets are used for each of them.

Suppose an operator has 15 MHz of spectrum for both up- and downlink transmissions. The system to be deployed is GSM. Each GSM carrier is spaced by 200 kHz, and 15 MHz supports 74 carriers, leaving one carrier bandwidth as a guard band. The operator requires that the microcell cluster provides approximately five times the capacity of the minicells. Accordingly, 24 carriers (approximately equivalent to 5 MHz) are assigned to the minicells, giving 2 carriers/sector, or 15 traffic channels/sector with one channel dedicated to signaling. For mobile telephony, with a blocking probability of 2 percent, the total traffic carried by the five minicells is 135 E. The microcells have 50 carriers, and the nine microcells can be arranged in a four-cell reuse. We arrange for seven microcell BSs to have 13 carriers and two microcells to have 11 carriers, corresponding to 95 and 80 traffic channels per site, after allowing approximately 10 percent of the channels for signaling. The total traffic carried by the microcells for a 2 percent blocking probability is 713 E. Observe that the microcells receive twice the bandwidth assigned to the minicells, but carry five times the traffic.

Also, the 135E minicellular traffic may all come from the street level, yielding a potential capacity of 848 E when combined with the microcellular traffic, or from a mixture at different elevations. Notice also that the microcells will provide coverage to many of the high floors in buildings in their immediate vicinity. Defining the spectral efficiency, η, in Erlang/MHz/km^2, the value for η for the



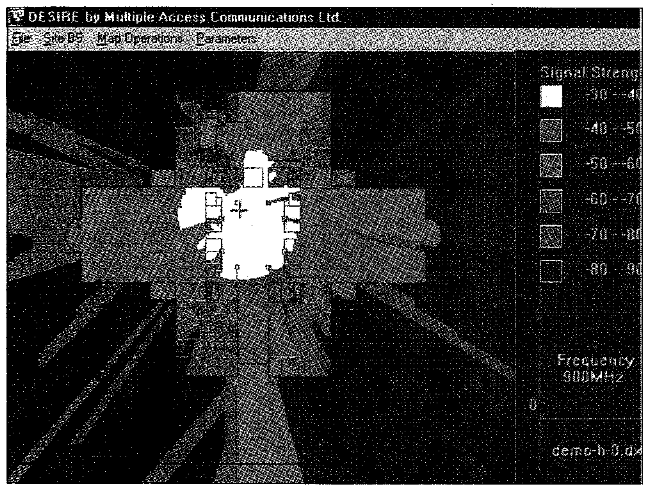
■ **Figure 17.** *Plan of a building.*



■ **Figure 18.** *Siting a street microcell on the wall of the building.*

minicells is 135/5/4, equal to 6.75, while that for the microcellular cluster is approximately 100 because the area occupied by the microcells is only about a fifth of that occupied by the minicells.

For the exclusively minicellular network shown in Fig. 8, where the network has acceptable performance only at ground level, the same 74 carriers are shared between 12 sectors, and there are three clusters of four cells. In each cluster, ten sectors have six carriers and two sectors have seven carriers. Allowing 10 percent for signaling and 2 percent blocking probability, the total traffic carried by the network is 1260 E, and $\eta = 21$. Thus, the arrangement of Fig. 8 is carrying more traffic at ground level than the arrangement shown in Fig. 14, but can only be used in certain locations at higher elevations, as indicated by Fig. 12. The arrangement of Fig. 14 is focused on where the traffic is generated, and there it has enormous spectral efficiency compared to that handled by the minicells, and the minicellular layer provides excellent conditions at higher elevations. Planning is simpler because of channel set partitioning. Notice that we may continue tessellating microcellular clusters, although with higher reuse [6], in the arrangement shown in Fig. 14. This will result in enormous spectral efficiencies and carried traffic levels. This cannot be done with the all-minicell network of Fig. 8, where deploying more minicells will rapidly increase co-channel interference to unacceptable limits, thereby curtailing carried traffic and spectral efficiency.



■ **Figure 19.** *The coverage outside a building due to an indoor picocell.*

Street Microcells and Indoor Picocells

Microcellular BSs may be attached to the walls of buildings or located on lampposts. Although these BSs are primarily designed for street coverage, their transmissions do penetrate into buildings, where they act as picocells. In order to predict these picocells in an accurate way we need to know the plans of the buildings and constructional details. Figure 17 shows the plans of a building where the green lines represent metalized glass that inflicts a high penetration loss of 30 dB, while the magenta lines represent plane glass whose loss is only 6 dB. The red, blue, and white lines correspond to walls made of breeze blocks, doors, and pillars, resulting in signal losses of 10, 2, and 15 dB, respectively.

Suppose we site a street microcell on the corner of the building, as indicated by the cross in Fig. 18. The resulting street and indoor coverage[2] shows that an irregular-shaped indoor picocell is created within the building, as well as strong coverage along the street. The coverage inside the building would have been greater if the outside walls had been made of brick or plate glass instead of metalized glass. Whereas a microcellular street BS will often provide good coverage within the nearest office to its location, the indoor picocellular BS may generate irregular coverage in the street microcell. This is illustrated by the coverage plot displayed in Fig. 19, where the signal level leaves the building in shafts of energy. The operator may have to plan for combinations of indoor picocells and adjacent street microcells (as well as oversailing minicells). Although we have only shown the coverage on the ground floor in Figs. 18 and 19, there is coverage on parts of the higher floors due to both the indoor and outdoor BSs. Frequency planning in this situation is far from simple.

Conclusions

As the demand for mobile services increases, extra capacity must be obtained by decreasing the size of cells. Small cells can only be realized by enlisting the help of the buildings, not treating them as some unwanted clutter. We have shown that cells must be planned in three dimensions with tools that rely on accurate 3D maps. Consideration has been given to channel set sharing, where the weak link in terms of interference is between minicellular (or microcellular) BSs and MSs in microcells. An all-minicellular network was exam-

[2] *Plot provided by DESIRE, an indoor planning tool from Multiple Access Communications Ltd.*

ined, as well as a network having both minicells for high rise buildings and microcells for street coverage. The latter network employed channel set partitioning. By this method huge volumes of traffic can be carried at street levels at high spectral efficiency by merely using contiguous clusters of microcells. Although we have discussed two-tier arrangements of cells, it is evident that many tiers can be planned. We briefly described how street microcellular BSs can provide indoor picocells, and how indoor BSs may influence street microcells. The three-dimensional radio prediction planning tool also enables received signal levels and SIR levels around buildings to be determined, enabling coverage within buildings by remote minicells to be estimated on a per-floor basis.

The planning tools are in place to design the high-capacity networks needed for the small city cells essential for UMTS. However, the realization of these small cells needs low-cost BSs, and their interconnections to the network routers and switches. The innate cost of BSs is low, but there are currently profound difficulties in providing and installing low-cost optical or radio links to interconnect them to the fixed part of the mobile network. With increasingly ubiquitous deployment of optical networks, we expect that optical fibers will ultimately be the preferred method of supporting small cell BSs on a LAN-type basis.

References

[1] S. Chia, "The Universal Telecommunication System," *IEEE Commun. Mag.*, Dec. 1992, pp. 54–63.

[2] J. Rapeli, "UMTS: Targets, System Concept and Standardization in a Global Framework," *IEEE Commun. Mag.*, Feb. 1995, pp. 20–28.

[3] J. E. Padget, C. G. Günther, and T. Hattori, "Overview of Wireless Personal Communications," *IEEE Commun. Mag.*, Jan. 1995, pp. 28–41.

[4] R. Steele, "The Therapy of Percy Comms: A Dialogue on PCS Issues," *Int'l. J. Wireless Info. Networks*, vol. 2, no. 3, 1995, pp. 123–32.

[5] W. T. Webb, "Sizing Up the Microcell for Mobile Radio Communications," *IEE Elect. and Commun.*, vol. 5, no. 3, June 1994, pp. 133–40.

[6] R. Steele *et al.*, "Teletraffic Performance of GSM900/DCS1800 in Street Microcells," *IEEE Commun. Mag.*, Mar. 1995, pp. 102–8.

[7] A. Emmerson, "Planning," *Land Mobile*, Sept. 1995, pp. 21–27.

[8] J. M. Keenan and A. J. Motley, "Radio Coverage in Buildings," *BT Tech. J*, vol. 8, no. 1, Jan 1990, pp. 19–24.

Biographies

SHIRIN DEHGHAN received an M.Eng. degree in electronics from Southampton University in 1993. She is the radio planning manager at Multiple Access Communications Ltd. Her main activity at MAC Ltd has been the research and development of radio propagation algorithms for cellular application in dense urban environments.

RAYMOND STEELE [F] (rs@macltd.demon.co.uk) is chairman of Multiple Access Communications Ltd. (http://www.macltd.demon.co.uk), and head of the Communications Research Group in the Department of Electronics and Computer Science at Southampton University. He received a B.Sc. degree in electrical engineering from Durham University, England, in 1959, and Ph.D. and D.Sc. degrees from Loughborough University of Technology, England, in 1975 and 1983, respectively. Before attaining his B.Sc., he was an indentured apprentice radio engineer. After research and development posts with E K Cole, Cossor Radar and Electronics, and Marconi, he joined the lecturing staff at Royal Naval College, London. He moved to Loughborough University in 1968, where he lectured and directed a research group in digital encoding of speech and picture signals. During the summers of 1975, 1977, and 1978 he was a consultant to the Acoustics Research Department at Bell Laboratories in the United States, and in 1979 he joined the company's Communications Methods Research Department, Crawford Hill Laboratory, New Jersey. He returned to England in 1983 to become professor of communications in the Department of Electronics and Computer Science at the University of Southampton, a post he retains. From 1983 to 1986 he was a nonexecutive director of Plessey Research and Technology, and from 1983 to 1989 a consultant to British Telecom Research Laboratories. In 1986 he formed Multiple Access Communications Ltd, a company concerned with digital mobile radio systems. He is the author of the book *Delta Modulation Systems* (New York: Halsted, 1975), editor of the book *Mobile Radio Communications* (IEEE Press and John Wiley, 1992), co-author of *Source-Matched Mobile Communications* (IEEE Press and John Wiley, 1995), and author of over 190 technical publications. He is the editor of a series of books on digital mobile communications, and is writing two books in the series. Professor Steele and his co-authors were awarded the Marconi Premium in 1979 and 1989, and the *Bell System Technical Journal*'s Best Mathematics, Communications, Techniques, Computing and Software, and Social Sciences Paper in 1981. He is also a senior technical editor of *IEEE Communications Magazine*, and a member of the advisory board of *IEEE Personal Communications* and the *International Journal of Wireless Information Networks*. He is a Fellow of The Royal Academy of Engineering, a Fellow of the IEE, and a member of the IEEE Avant Garde.