



Doufexi, A., Tameh, EK., Molina, A., Nix, AR., & Armour, SMD. (2003). Hotspot wireless LANs to enhance the performance of 3G and beyond cellular networks. *IEEE Communications Magazine*, 41(7), 58 - 65. <https://doi.org/10.1109/MCOM.2003.1215640>

Peer reviewed version

Link to published version (if available):
[10.1109/MCOM.2003.1215640](https://doi.org/10.1109/MCOM.2003.1215640)

[Link to publication record in Explore Bristol Research](#)
PDF-document

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

Hotspot Wireless LANs to Enhance the Performance of 3G and Beyond Cellular Networks

*Angela Doufexi, Eustace Tameh, Andrew Nix, and
Simon Armour, University of Bristol
Araceli Molina, ProVision Communications*

ABSTRACT

At present, WLANs supporting broadband multimedia communications are being developed and deployed around the world. Standards include HIPERLAN/2 defined by ETSI BRAN and the 802.11 family defined by the IEEE. These systems provide channel adaptive data rates up to 54 Mb/s (in a 20 MHz channel spacing) over short ranges up to 200 m. The HIPERLAN/2 standard also specifies a flexible radio access network that can be used with a variety of core networks, including UMTS. It is likely that WLANs will become an important complementary technology to 3G cellular systems and will typically be used to provide hotspot coverage. In this article the complementary use of WLANs in conjunction with UMTS is presented. In order to quantify the capacity enhancement and benefits of cellular/hotspot interworking we have combined novel raytracing, software-simulated physical layer performance results, and optimal base station deployment analysis. The study focuses on an example deployment using key lamppost mounted WLAN access points to increase the performance (in terms of capacity) of a cellular network.

INTRODUCTION

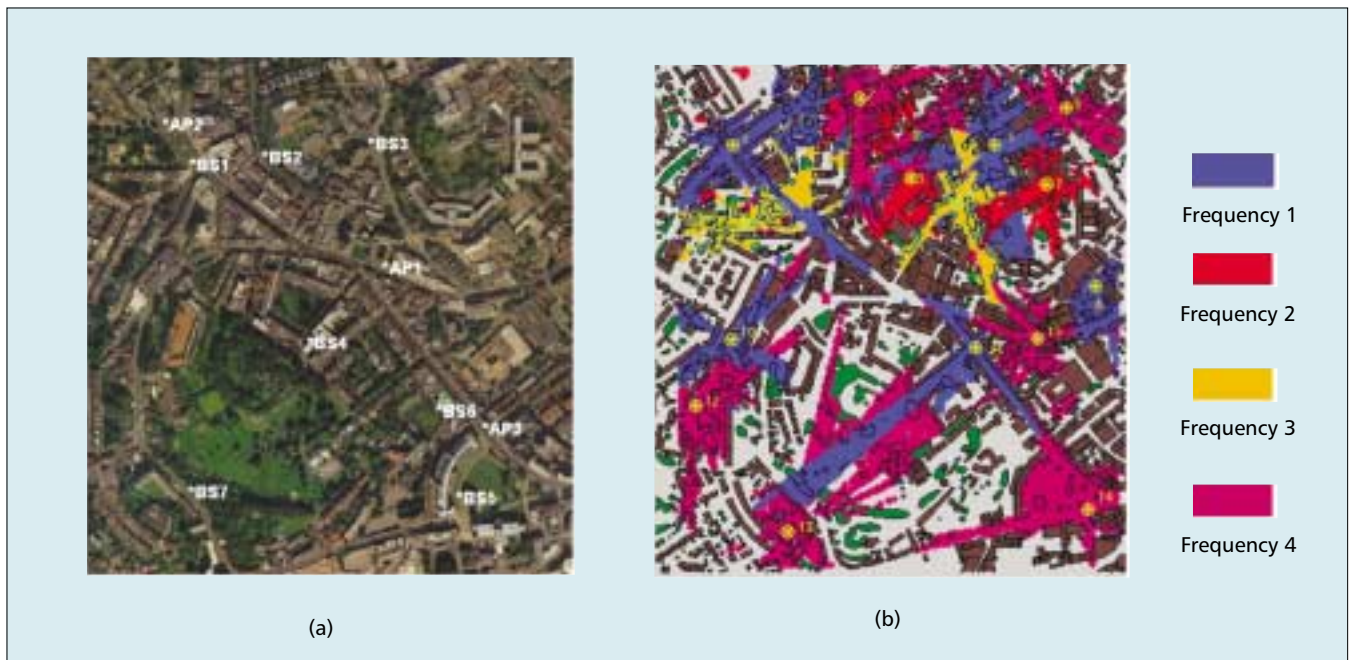
Third-generation (3G) cellular services are now active in a number of countries around the world. In the near future, users are expected to demand higher-rate multimedia services and ubiquitous communications. To achieve these goals, 3G networks will evolve to provide higher data rates and new radio access technologies. One widely anticipated form of evolution is the complementary use of wireless LAN (WLAN) hotspots. Ultimately, beyond 3G networks will expand to offer data rates in excess of 100 Mb/s and interwork with a number of technologies

including satellite communications, WLANs, and digital broadcast technologies. Eventually, such networks will provide integrated and seamless services via a common IP-based network [1, 2].

The beyond 3G environment is very complex and involves several aspects such as joint authentication, authorization, and accounting, seamless handovers between different networks/services, and the use of sophisticated terminals. However, this article ignores such higher-layer aspects and instead attempts to quantify the capacity benefits offered by interworking Universal Mobile Telecommunications System (UMTS) and WLAN hotspot technology. The issues involved are graphically illustrated through the use of an example deployment in the center of Bristol, United Kingdom.

WLANs provide high-speed wireless connectivity between PCs, laptops, and other equipment in corporate, public, and home environments. HIPERLAN/2 [3–5], defined by the European Telecommunications Standards Institute project on Broadband Radio Access Networks (ETSI BRAN), and IEEE 802.11a [6] are WLAN standards that support multiple transmission modes providing data rates up to 54 Mb/s where channel conditions permit.

Applications for WLAN technology include wireless data access within the home and business environments. WLANs will support wire-free high-speed Internet access and the distribution of high-definition audio and video streams. In the near future, WLANs will offer high-speed hotspot extensions to conventional cellular radio access networks. In particular, HIPERLAN/2 offers different convergence layers facilitating access to various core networks such as IP and UMTS. This interworking structure enables the interaction of HIPERLAN/2 with evolving 3G mobile networks to be defined in a flexible and future-proof manner [7].



■ **Figure 1.** a) Locations of seven BSs and three APs; b) locations and example frequencies for 15 APs.

Presently, two approaches have been proposed for interconnection of WLAN and 3G networks: tight coupling and loose coupling [2]. A tight coupling scheme would offer seamless handover and the same level of security in WLAN and 3G networks. This approach requires an interface for interconnection of the WLAN to the 3G core network. On the other hand, a loose coupling scheme would rely on IP protocols to organize mobility and roaming between access networks. In this case there will be a common customer and authentication procedure. Interworking between the WLAN and the core network will be performed between the authentication, authorization, and accounting server and the home location register [2].

Hence, within the context of 3G cellular systems, WLANs are now seen as a complementary technology that can be used to provide users with high-data-rate services in localized high-traffic-density locations (e.g., city centers and business districts). Handovers will be possible between 3G cellular access networks and WLAN access points. Although limited to small dense urban environments and pedestrian mobility, the increased capacity offered by WLAN hotspots is substantial. HIPERLAN/2 operates as a connection-oriented wireless link. As such, it supports the differentiated quality of service (QoS) levels required for the transmission of various media. Relative to cellular terminals, WLANs achieve far higher bit rates but are restricted to small coverage zones. Hence, a user with a dual mode terminal will be able to take advantage of the higher data rates offered by WLAN hotspots while relying on the full range of 3G cellular features in more remote locations.

In order to quantify the capacity benefits offered to a cellular network making use of complementary WLAN technology, novel raytracing, software-simulated physical layer performance results, and optimal base station (BS) deployment

analysis have been applied to the complex inter-networking problem. The analysis focuses on an example deployment using key lamppost-mounted WLAN access points to increase the performance (in terms of capacity) of a conventional cellular network. It is assumed that the WLAN hotspots are overlaid on a microcellular UMTS network.

The structure of this article is as follows. We present the simulation tools used in this deployment and describe their interaction. Physical layer performance results for 5 GHz WLANs are presented, showing packet error rate (PER) and throughput results against signal-to-noise ratio (SNR). A propagation modeling tool was employed in the specified environment to provide point-to-multipoint analysis of the received signal levels at 2 GHz (UMTS) and 5 GHz (WLAN). We present coverage and throughput results for the entire hotspot overlay. We describe the system-level Monte Carlo simulation used to determine the integrated WLAN/3G capacity results. Finally, we discuss internetworking results and present our main conclusions.

THE SIMULATION SETUP

To study the use of hotspot WLANs as an enhancement to 3G cellular networks, this article focuses on a dense urban deployment where capacity requirements are at their highest. To quantify the problem, the simulated deployment of a high-capacity 3G network is first performed; this is followed by an integrated hotspot overlay. The article assumes the use of UMTS technology at 2 GHz and HIPERLAN/2 WLAN technology at 5 GHz. However, due to the similarity of the physical layers [4], the analysis presented here is also applicable to 802.11a with only a few minor modifications. With this in mind, a number of results based on IEEE 802.11a are also presented. A number of simulation tools previously developed by the authors [4, 5, 8, 9] were

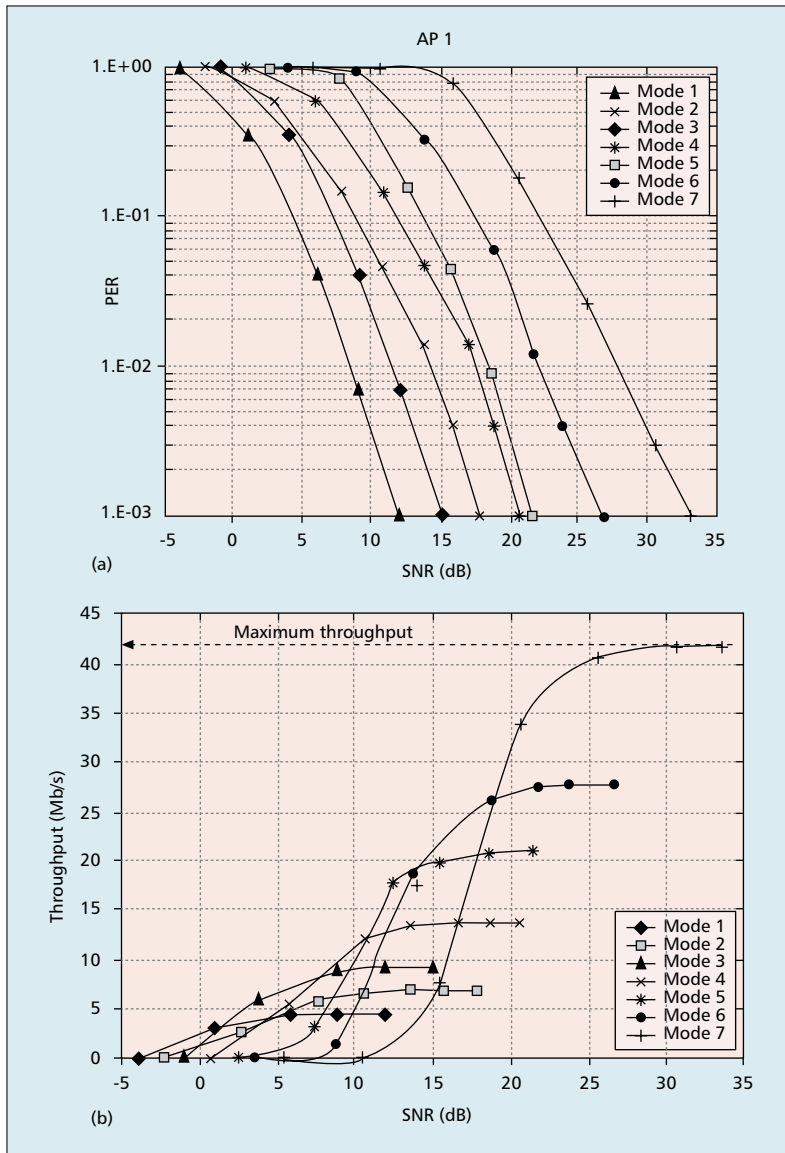


Figure 2. a) PER performance; b) throughput vs. SNR of AP1 for HIPERLAN/2.

combined in order to evaluate potential coverage and capacity gains. These include:

- A propagation modeling tool
- A site optimization tool
- A frequency planning algorithm
- A WLAN physical layer simulator
- A 3G/WLAN system-level Monte Carlo simulator for capacity analysis

Each of these algorithms is described in the following subsections.

THE PROPAGATION MODEL

A state-of-the-art deterministic propagation model is used to provide the channel data required in the evaluation of both the 5 GHz HIPERLAN/2 and 2 GHz cellular networks. The deterministic model uses geographic data (terrain, building, foliage, and ground cover) to predict power as well as time, frequency, and spatial dispersion in the radio channel [9]. It is optimized for intracellular coverage as well as intercellular (interference) predictions between different cells

in a mixed-cell network. Propagation data is supplied for each potential site. This data is then provided as an input to the site optimization module and is used to optimize the number and locations of cellular and WLAN sites. Complex channel impulse response data from the propagation model at the optimized WLAN access points is additionally provided and used in the physical layer simulations described later.

THE SITE OPTIMIZATION MODULE

A novel optimization algorithm that allows the optimum positioning of cellular and WLAN sites has been implemented. This algorithm is based on a combinatorial approach previously developed for conventional cellular planning [8]. The new optimization method has been redesigned to solve the problem of optimizing cellular and/or WLAN site locations and densities for different configurations and environments.

To solve the optimization/placement problem, the algorithm uses an overspecified and user-defined group of possible sites. A complex analysis based on combinatorial theory is then performed before the final set of sites is chosen. To perform this analysis, the algorithm utilizes the data supplied by the propagation model to allow selection of an optimal set of sites [8].

For the deployment of WLAN hotspots, potential access point (AP) locations were selected from available lamppost locations, while conventional locations were used for the deployment of UMTS base stations. The 3G study was performed at 2 GHz, assuming omnidirectional antennas located at a height of 5 m and with a transmit power of 30 dBm. The hotspot overlay was performed at 5 GHz, with omnidirectional antennas at a height of 5 m and AP transmit powers of 23 dBm and 30 dBm.

The optimization process was performed over 1 km² of central Bristol. Seven UMTS BSs were chosen to fulfill the coverage requirements of the area (90 percent coverage). UMTS optimization was performed to achieve this level of area coverage using the minimum number of BSs. In the first case, three WLAN sites (each with a nominal 200 m radius) were chosen to cover key sections of the main commercial/business area. Figure 1a shows the locations of the chosen 3G base stations (denoted “*BS_n”) and WLAN APs (denoted “*AP_n”) on an aerial photograph of Bristol. In order to provide high-data-rate coverage over the entire 1 km² region, a second optimization process was performed resulting in 15 WLAN APs. The resulting hotspots then covered 90 percent of the required area. The locations of the 15 WLAN APs are shown in Fig. 1b. Note that Figs. 1a and 1b depict the same area.

FREQUENCY ALLOCATION

The HIPERLAN/2 standard supports the use of dynamic frequency selection (DFS) in order to minimize interference when multiple APs are employed in the network. Currently, 11 channels are available for outdoor use in the license exempt band between 5.470–5.725 GHz with an equivalent isotropic radiated power (EIRP) limit of 30 dBm. However, it is not known if they will all be available for single operator use. In this article we assume that a limited number of hotspot frequencies are available and

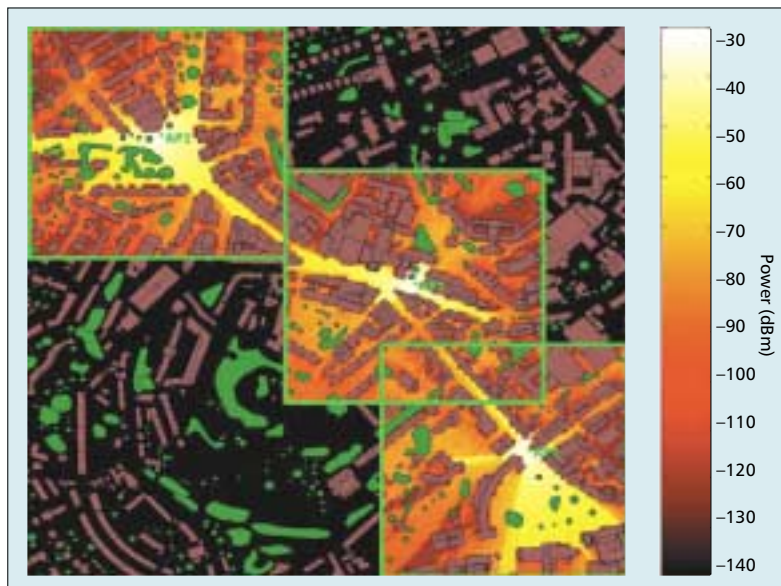
make use of a frequency allocation tool to determine the minimum number of hotspot carriers required for a given number of APs and a given C/I ratio. This analysis is necessary per deployment to ensure that the hotspot DFS algorithm can reach a satisfactory solution. The frequency allocation method makes use of combinatorial theory as well as the well-known greedy algorithm [8]. We assume that the three APs in the first scenario operate at different frequencies, so there is no interference between overlapping hotspots. The frequency planning algorithm was used for the case of 15 densely located APs, and the results indicate that a minimum of four carriers are required in order to achieve a minimum carrier-to-interference ratio (C/I) of 10 dB. Figure 1b shows a sample allocation of the four frequencies in this larger network. In practice, these frequencies are automatically allocated via the DFS algorithm.

A PHYSICAL LAYER SIMULATOR FOR WLANs

In order to evaluate the performance of WLAN hotspots in an outdoor environment, link-level simulations were performed utilizing channel information from the propagation model. A detailed physical layer (PHY) software simulation of HIPERLAN/2 and 802.11a was developed previously by the authors; results were presented in [4]. For the purposes of this article, the software simulation was employed to evaluate performance in terms of PER and throughput vs. SNR. Complex impulse response (CIR) channel data was provided for the areas of interest using the propagation tool described earlier.

The physical layers of HIPERLAN/2 and IEEE 802.11a/g are based on the use of coded orthogonal frequency-division multiplexing (COFDM). COFDM is used to combat frequency-selective fading and randomize the burst errors caused by a wideband fading channel. OFDM modulation is implemented by means of an inverse fast Fourier transform (IFFT). Forty-eight data symbols and four pilots are transmitted in parallel in the form of one OFDM symbol. In order to prevent intersymbol interference (ISI), a guard interval is implemented by means of a cyclic extension. When the guard interval period is equal to or longer than the excess delay of the radio channel, ISI is eliminated.

Importantly, the hotspot physical layer provides several modes, each with a different coding and modulation configuration [4]: mode 1: binary phase shift keying (BPSK) 1/2 rate; mode 2: BPSK 3/4 rate; mode 3: quaternary PSK (QPSK) 1/2 rate; mode 4: QPSK 3/4 rate; mode 5: 16-quadrature amplitude modulation (QAM) 9/16 rate; mode 6: 16-QAM 3/4 rate; mode 7: 64-QAM 3/4 rate. These are selected by a *link adaptation* scheme. Link adaptation schemes may use a variety of link quality measurements such as PER and received signal strength. The link throughput when retransmission is employed is given by the following approximation: $Throughput = R(1 - PER)$, where R and PER are the bit rate and packet error rate for a specific mode, respectively [4, 5]. In this article a link adaptation scheme has been used in which the mode with the highest throughput is chosen for each instantaneous SNR value. To obtain the throughput after the medium access control (MAC) layer, MAC overheads are also considered [5].



■ Figure 3. Coverage map for three outdoor APs with 30 dBm transmit power.

THE CAPACITY SIMULATOR

This analysis is performed to quantify the performance improvement (in terms of throughput and area coverage) arising from UMTS/hotspot interworking in a practical and realistic operating environment. The achievable data rate and coverage is evaluated for a number of hotspot locations. The propagation modeling tool is employed to provide path loss (or received signal strength) and channel data (complex impulse responses, CIRs) for the outdoor environment. Coverage and interference maps can then be generated for each HIPERLAN/2 AP. Subsequently, the throughput results are used to translate the received signal power or SNR into an achievable data rate for HIPERLAN/2 (or 802.11a) hotspots.

A system-level Monte Carlo simulation was used to analyze the two integrated 3G/hotspot scenarios: three APs and 15 APs. The 3G simulation assumed a 3.84 Mcchip/s UMTS terrestrial radio access (UTRA) time-division duplex (TDD) type system [10] with fixed and ordered time slot allocation, but with asymmetric sharing of slots between the uplink (UL) and downlink (DL). Three user classes were considered: for 3G, class 1 users support voice at 15 kb/s, class 2 users support data at 144 kb/s, and class 3 users support data at 384 kb/s. However, since hotspots are intended to support higher bit rate (broadband) users, the classes of users here were changed to 144 kb/s (class 1), 384 kb/s (class 2), and 2 Mb/s (class 3). The traffic mix is specified as 60 percent class 1, 30 percent class 2, and 10 percent class 3 for both 3G and WLAN users. Although all users are assumed to have dual-mode terminals (i.e., they can access both 3G and hotspot services on the same terminal), voice users are restricted to the 3G network, and 2 Mb/s requests can only be supported on the hotspot overlay. Users are uniformly deployed in the 1 km × 1 km area of Bristol, and the propagation model is used to determine path losses to the various BSs and APs as well as losses between the BSs for interference calculations. Users who fall within the coverage

area of a hotspot AP are *connected* to that AP if their required data rate is not above the maximum achievable rate for that location and the available hotspot capacity is sufficient to accommodate the user. The available capacity for each hotspot AP is determined from the mean of the data rates in the coverage area. Users who cannot connect to a hotspot WLAN (or require a voice service) are passed on to the 3G network. Admission to the 3G network is controlled by a noise rise limit at the BS, and time slots and orthogonal

variable spreading factor (OVSF) codes are allocated in the UL and DL. Joint detection is implemented in the UL to reduce intracell interference at the BS. Power control is also implemented to ensure that specified link quality targets (E_b/N_0 targets for the different data rates) are maintained in the UL and DL. Two cases are examined: the first includes data rates up to 2 Mb/s at the hotspot; the second restricts hotspot data rates to 384 kb/s.

WLAN PHYSICAL LAYER PERFORMANCE RESULTS

After processing the channels obtained from the propagation modeling tool for the WLAN hotspot sites, link level simulations were performed. For each WLAN site, ~2000 CIRs corresponding to a mixture of line-of-sight and non-line-of-sight points were obtained in a specified area around the AP. These channel realizations were then used to obtain an average PER performance for the given region. The mean rms delay spread in the vicinity of AP1 was $\tau_{\text{rms}} = 55$ ns. Figure 2, shows physical layer performance results for HIPERLAN/2 for AP1 in terms of PER and throughput vs. SNR. Note that MAC overheads for HIPERLAN/2 have also been taken into account when calculating the throughput [4, 5]. The maximum throughput after MAC overheads is 42 Mb/s for HIPERLAN/2. The maximum throughput after MAC overheads for IEEE 802.11a differs from that shown in Fig. 2 and depends on the packet size (since this standard supports variable packet sizes). When a packet size of 1500 bytes is used, the maximum throughput is 31 Mb/s [4, 5]. The same procedure was repeated for the other APs, and results obtained for both HIPERLAN/2 and 802.11a. To map the throughput vs. SNR results to achievable throughput in our site-specific region it is necessary to relate the signal power at every location to an SNR value. To translate the received power to SNR, Eq. 1 was used where NF represents the noise figure (8 dB), K is Boltzmann's constant, T is the temperature (290°K) and B is the bandwidth:

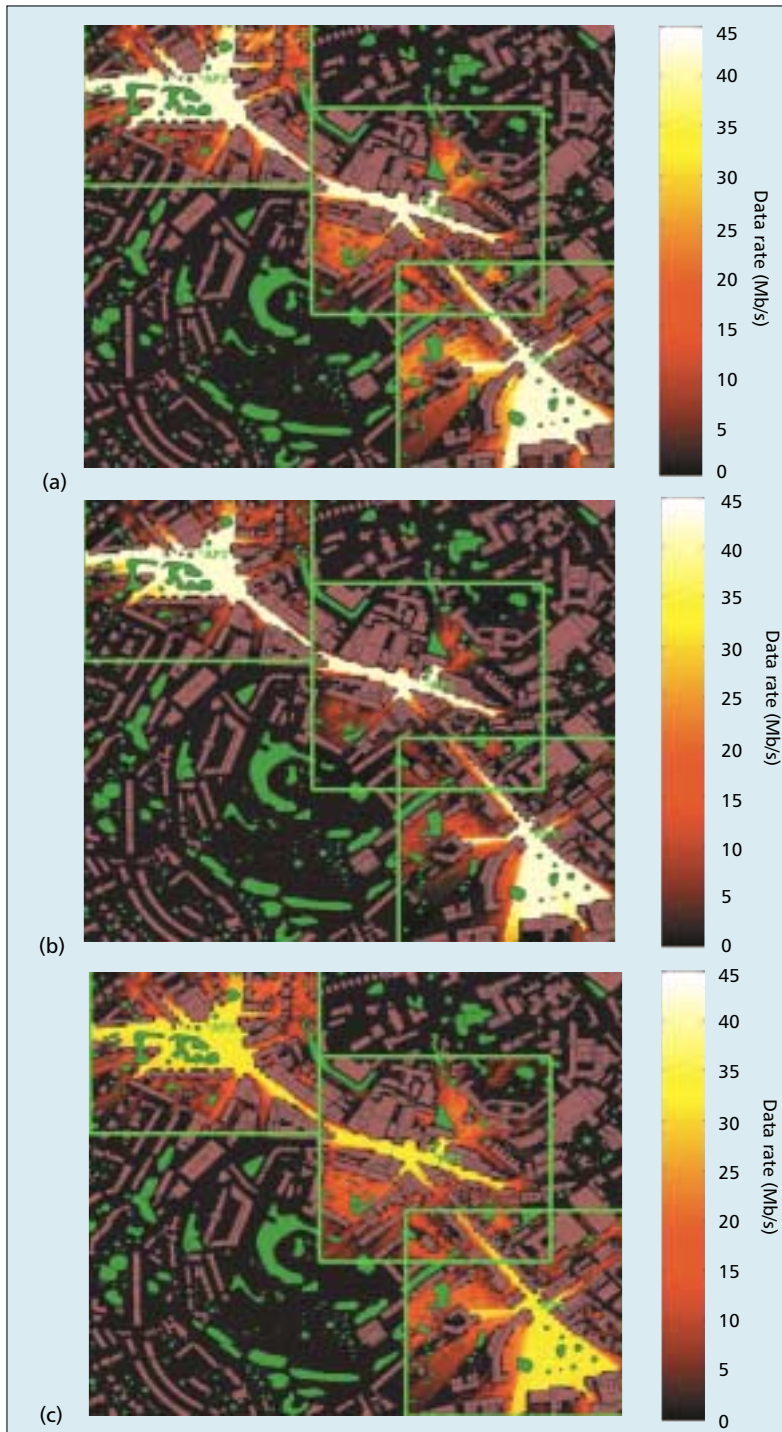
$$SNR \text{ (dB)} = Rx \text{ Power (dBm)} - KTB \text{ (dBm)} - NF \text{ (dB)} \quad (1)$$

COVERAGE AND THROUGHPUT ANALYSIS

As discussed earlier, we used a site-specific deterministic propagation model to provide realistic propagation data for the 5 GHz hotspots shown in Figs. 1a and 1b. Based on this predicted data, the throughput was simulated assuming either the HIPERLAN/2 or IEEE 802.11a WLAN standard. The resulting output provides a unique insight into the maximum achievable hotspot data rate at each location in the environment.

Considering the first case (three hotspot APs), Fig. 3 shows the coverage achieved for predefined areas around each hotspot assuming transmit powers of 30 dBm. Obviously, a reduced transmit power of 23 dBm leads to a corresponding reduction in received signal power (and hence area coverage and throughput).

Figure 4 compares the throughput achieved



■ **Figure 4.** Throughput map for a) HIPERLAN/2, 30 dBm transmit power; b) HIPERLAN/2, 23 dBm transmit power; c) IEEE 802.11a, 30 dBm transmit power and 1500-byte packets.

for HIPERLAN/2 with transmit powers of 30 dBm and 23 dBm and for IEEE 802.11a with transmit power of 30 dBm (packet size of 1500 bytes). Note that coverage analysis is restricted to outdoor locations. The reduced throughput of 802.11a is due to the higher overhead of the standard, which results in a maximum data rate of 31 Mb/s as described in the previous section. Figure 5 shows the modes employed at every location in the hotspot overlay for both HIPERLAN/2 and IEEE 802.11a. Mode 0 implies that there is no coverage available at this point. It can be seen that mode 7 is used for a high proportion of the area, and the modes degrade rapidly with increasing distance from the hotspot. This effect is due to the propagation characteristics at 5 GHz in a high-density urban microcell (where path loss increases rapidly with distance).

Figure 6 shows the corresponding coverage, throughput, and mode distribution for the case of 15 HIPERLAN/2 hotspots. It can be seen that most of the 1 km × 1 km area is covered by the 15 APs (with four frequencies), and higher modes (throughput) are used in a higher proportion of the area.

The above results are further illustrated in Fig. 7, which compares the coverage area for specific data rates in the three AP and 15 AP networks. Here the areas refer to the total coverage from all APs in the hotspot network. Results for HIPERLAN/2 show that the area supporting data rates greater than 15 Mb/s increases from 62,000 m² to 95,000 m² as the hotspot transmit power rises from 23 to 30 dBm. For the higher transmit power (30 dBm), IEEE 802.11a hotspots would cover only 74,000 m² at this bit rate. Interestingly, for data rates beyond 25 Mb/s, HIPERLAN/2 at 23 dBm transmit power covers a larger area than IEEE 802.11a at 30 dBm. Naturally, the area covered using 15 hotspots is considerably larger for all throughput levels. The throughput can be seen to peak at 42 Mb/s (assuming a single user in that hotspot). As a comparison, for the area where rates exceed 13 Mb/s in the three-AP scenario, this now increases to beyond 38 Mb/s in the 15 AP network.

CAPACITY ANALYSIS

Table 1 shows the capacity results for the integrated UMTS/hotspot network. The number and class of users supported in the mixed traffic network for a 95 percent grade of service is indicated in Table 1 for the scenarios described earlier. The values for WLAN represent either UL or DL connections; for 3G the numbers refer to actual users (i.e., combined UL and DL connections). Hotspot capacity is quoted as the number of connections since the capacity is expected to be asymmetrically dominated by DL connections.

As expected, the total number of users supported in the 3G network stays approximately the same for all scenarios, with only a single 384 kb/s user being supported at each BS. Not surprisingly, when 2 Mb/s connections are carried over the hotspot network, fewer lower-bit-rate connections (classes 1 and 2) are supported than when user rates are restricted to 384 kb/s. However, the spectral efficiency of the entire hotspot overlay remains approximately constant (ignoring the additional MAC overheads that result

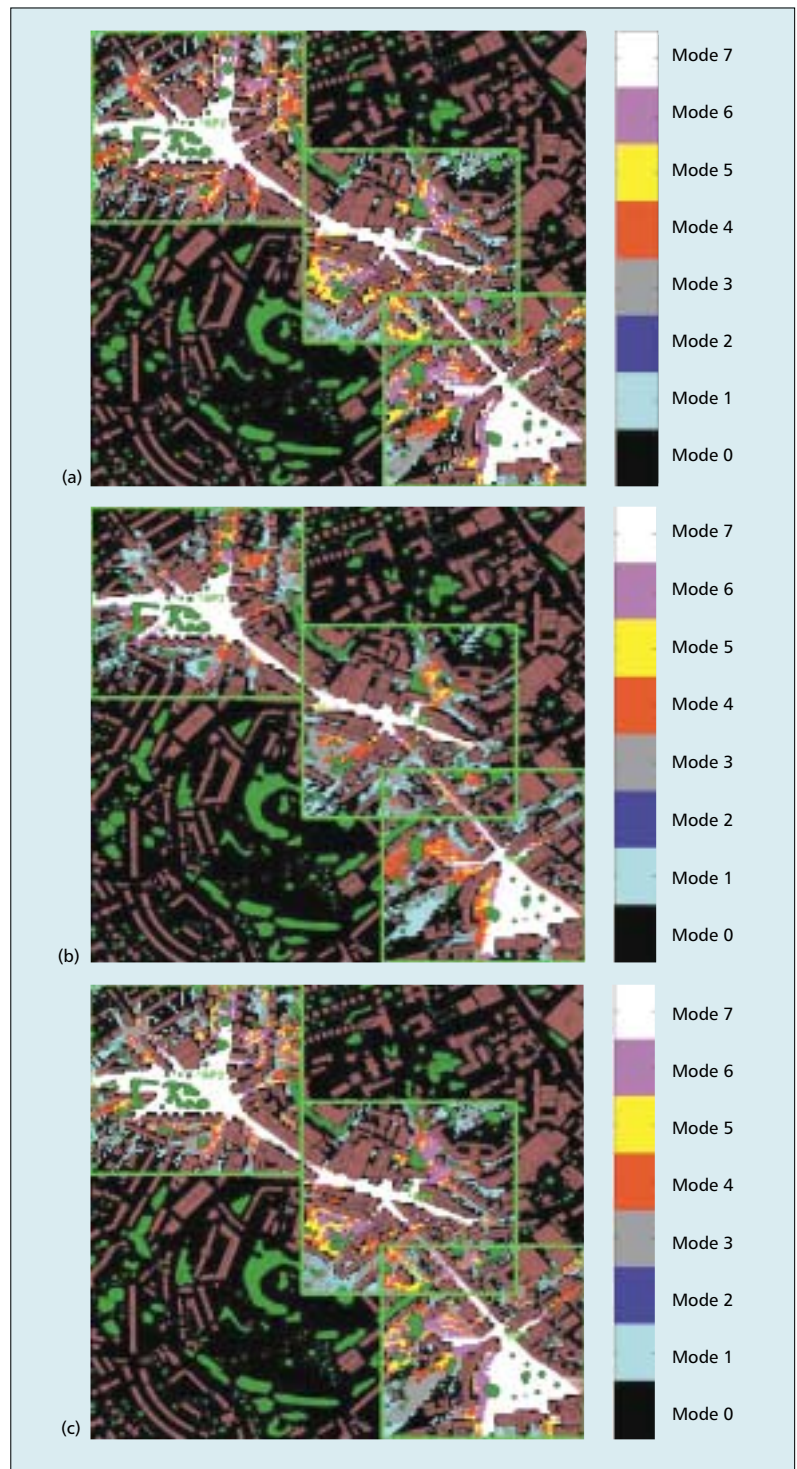


Figure 5. Mode map for a) HIPERLAN/2, 30 dBm transmit power; b) HIPERLAN/2, 23 dBm transmit power; c) IEEE 802.11a, 30 dBm transmit power and 1500-byte packets.

from a greater number of connections).

For a hotspot transmit power of 23 dBm the total number of connections is lower than for the higher-power (30 dBm) case. This results from lower mean throughput due to lower received power. For example, when 2 Mb/s connections are carried over the hotspots, the total number of connections decrease from 54 to 45 per AP as the transmit power drops from 30 to 23 dBm.

The higher coverage and throughput achieved using 15 hotspots allow a much larger number of connections to be supported compared to the three-hotspot scenario. This is further illustrated by the higher spectrum efficiency (up to 1.68 b/s/Hz/AP) observed for the 15-AP case. Continuing from the previous example, the total number of connections per AP now increases to 75 for the case with 15 APs. This results in a total of over 1000 connections in the 1 km × 1 km area supported by the hotspot overlay. Additionally it can be observed that WLAN hotspots

have the capability to support 2 Mb/s and higher connections, in contrast to the very restricted bit rates using the conventional 3G network.

CONCLUSIONS

In this article channel data from a 3D site-specific propagation model together with physical layer and system-level simulation tools have been used to simulate the coverage, throughput, and capacity of an integrated 3G/hotspot system in an urban microcellular environment. The BS and AP locations were optimized using a site optimization algorithm, and two cases were examined for the hotspot overlay: the first involved three APs, and the second made use of 15 APs. For the larger network, a frequency allocation algorithm was used to verify that four frequencies were sufficient in the hotspot layer.

Coverage, throughput, and transmission mode distribution maps were produced for the different cases, including results for both HIPERLAN/2 and IEEE 802.11a with variable AP transmit powers. The area coverage in the hotspot layer was analyzed for different scenarios and transmit powers. It was seen that at higher data rates the HIPERLAN/2 standard covers a larger area than IEEE 802.11a. As expected, 15 APs were shown to cover a large proportion of the network area, and high peak rates (up to 42 Mb/s) were available at many locations. Overall, hotspot data support is considerably higher than even the highest 3G rates; this will enable the transport of intensive multimedia applications (e.g., video, 3D graphics) over the network.

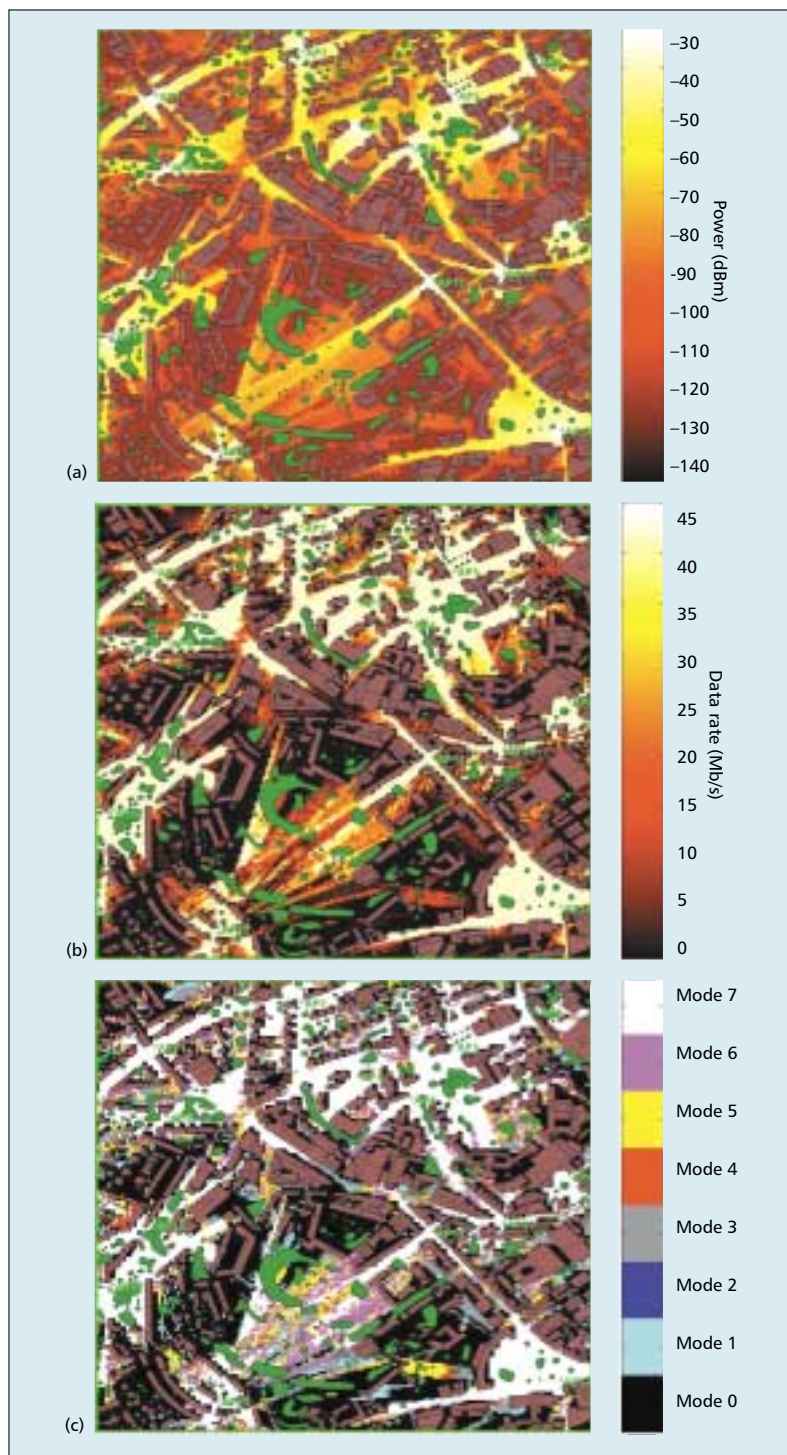
Capacity has been shown to significantly increase when interworking between hotspots and 3G networks is employed. This is particularly true when a high percentage of the area is covered by the hotspot network. It was shown that over 1000 extra connections can be supported in a 1 km × 1 km area when 15 WLAN hotspots are deployed alongside the 3G network. To take advantage of such interworking, users are required to use dual mode terminals. This allows users to combine higher data rates in the hotspots with continuous coverage and high mobility via the cellular network. In dense urban areas where high populations require extra capacity, hotspots can be deployed to enhance data rates and relieve cellular congestion. The number of hotspots will mainly be determined by user demand with their exact locations ideally determined using site optimization tools.

ACKNOWLEDGMENTS

This work has been performed under the framework of the IST ROMANTIK project, which is funded by the European Union.

REFERENCES

- [1] Y. Kim et al., "Beyond 3G: Vision, Requirements, and Enabling Technologies," *IEEE Commun. Mag.*, vol. 41, no. 3, Mar. 2003, pp. 120–24.
- [2] J. De Vriendt et al., "Mobile Network Evolution: A Revolution on the Move," *IEEE Commun. Mag.*, vol. 40, no. 4, Apr. 2002, pp. 104–11.
- [3] ETSI, "Broadband Radio Access Networks (BRAN); HIPERLAN Type 2 Technical Specification; Physical (PHY) layer," Aug. 1999.
- [4] A. Doufexi et al., "A Comparison of the HIPERLAN/2 and IEEE 802.11a Wireless LAN Standards," *IEEE Commun. Mag.*, May 2002, vol. 40, no. 5, pp. 172–80.



■ **Figure 6.** a) Coverage; b) throughput; c) mode distribution for 15 HIPERLAN/2 APs with 30 dBm transmit power.

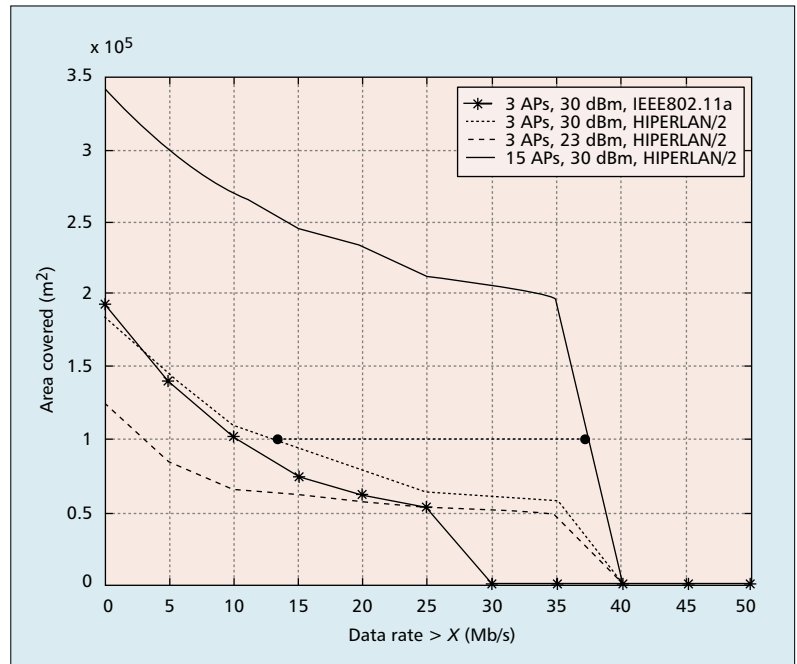
- [5] A. Doufexi *et al.*, "Throughput Performance of WLANs Operating at 5GHz Based on Link Simulations with Real and Statistical Channels," *IEEE VTC*, Spring 2001, Rhodes, vol. 2, pp. 766-70.
- [6] IEEE Std 802.11a/D7.0-1999, Part 11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High Speed Physical Layer in the 5 GHz Band."
- [7] ETSI TR 101 957, "Broadband Radio Access Networks (BRAN); HIPERLAN Type 2; Requirements and Architectures for Interworking between HIPERLAN/2 and Third Generation Cellular Systems," v. 1.1.1, Aug. 2001.
- [8] A. Molina, G. E. Athanasiadou, and A. Nix, "Cellular Network Capacity Planning Using the Combination Algorithm for Total Optimization," *IEEE VTC*, vol. 3, Tokyo, Japan, Spring 2000, pp. 2512-16.
- [9] E. K. Tameh and A. R. Nix, "A Mixed-Cell Propagation Model for Interference Prediction in a UMTS Network," *IEEE VTC*, Spring 2001, vol. 1, Rhodes, pp. 409-13.
- [10] ETSI, "UMTS UTRA (UE) TDD: Radio Transmission and Reception," 3GPP TS 25.102 v4.3.

BIOGRAPHIES

ANGELA DOUFEXI [M] (a.doufexi@bristol.ac.uk) graduated from the University of Athens (Greece) with a B.Sc. in physics in 1996. She received her M.Sc. in electronic engineering from Cardiff University, United Kingdom, in 1998. She then joined the Centre for Communications Research at the University of Bristol, where she received her Ph.D. in the area of WLANs in 2002. She was appointed a research associate at the University of Bristol in October 2001. She has worked at the European collaborative IST projects SATURN and ROMANTIK. Her research interests include OFDM systems, wireless LANs, space-time coding, and MIMO, as well as 4G communications systems.

EUSTACE TAMEH (tek.tameh@bristol.ac.uk) graduated from Keele University, United Kingdom, with a B.Sc. Hons. degree in electronic engineering and mathematics in 1994. He then joined the University of Bristol in September 1994, pursuing a Ph.D. in the area of wide area propagation prediction and the planning of mobile radio networks. Since 1997 he has worked as a research associate in the Centre for Communications Research at the University of Bristol, working on research projects in the areas of propagation modeling and cellular network design. His current research interests lie in the development of novel radio channel prediction tools, multisystem integration, and the development of new technologies for 3G and beyond networks.

ARACELI MOLINA (araceli.molina@provision-comm.com) received a B.Eng. in electronics and communication engineering in 1997 and a Ph.D. in electrical and electronic engineering in 2000, both from the University of Bristol. In December 2000 she joined ProVision Communications, where she is currently managing development work that includes various aspects of mobile communications including advance coding and modulation techniques, capacity analysis, and system performance evaluation techniques.



■ Figure 7. Throughput area distribution comparison.

Her research interests lie in the field of network planning and optimization tools for next-generation cellular technologies.

ANDREW NIX (andy.nix@bristol.ac.uk) received his B.Eng. and Ph.D. degrees from the University of Bristol in 1989 and 1993, respectively. He joined the lecturing staff at the university in 1992 and was promoted to professor of wireless communication systems in 2001. His research interests include broadband wireless communications, radiowave propagation modeling, and cellular network optimization. He leads the propagation modeling and wireless LAN groups.

SIMON ARMOUR [M] (simon.armour@bristol.ac.uk) received his B.Eng. degree from the University of Bath in 1996 and his Ph.D. degree from the University of Bristol in 2001. Following a period of postdoctoral research in the area of advanced WLAN technologies, he was appointed to the position of lecturer in software radio at the University of Bristol in 2001. His research interests include multicarrier modulation, software radio, WLANs/PANs, adaptive modulation and coding, and medium access control.

Scenario	WLAN connections /AP			WLAN SE (b/s/Hz/AP)	3G users per BS		
	144 kb/s	384 kb/s	2 Mb/s		15 kb/s	144 kb/s	384 kb/s
3 APs, EIRP = 30 dBm 2 Mb/s on WLAN	33	16	5	1.16	16	4	1
3 APs, EIRP = 30 dBm no 2 Mb/s on WLAN	64	25	0	1.15			
3 APs, EIRP = 23 dBm 2 Mb/s on WLAN	28	13	4	1.0			
3 APs, EIRP = 23 dBm no 2 Mb/s on WLAN	49	24	0	0.98			
15 APs, EIRP = 30 dBm, 2 Mb/s on WLAN	47	22	6	1.68			
15 APs, EIRP = 30 dBm, no 2 Mb/s on WLAN	82	40	0	1.65			

■ Table 1. Capacity for combined 3G and WLAN system.