Appendix A

DCA Simulation Model

This appendix documents a computer simulation of the performance of DCA algorithms in a 769km altitude LEO satellite system. The results of the simulations (presented in appendices B and C) show that DCA is able to realize 2.4 times the capacity of a geographically fixed frequency re-use plan in the LEO satellite radio environment and details the delays in processing handovers that can be expected when using the dynamic scheme.

A number of important observations regarding the implementation of Dynamic Channel Assignment algorithms were found through simulation and are discussed in chapter 7. It is found that there is an optimum limit to the number of spare channels that should be searched at handover and that allowing more thorough searches is counterproductive because it not only slows down handover execution but reduces the overall system capacity. It is also found that FESs must be able to communicate with multiple satellites at once to retain complete control of inter-satellite handovers. This avoids unacceptably long delays whilst the mobile terminal tries to find another satellite by itself.

A.1. Aims

The simulations were performed to verify the DCA algorithm and to compare its performance with a fixed re-use plan. The measures of performance sought were the capacity of the system and the grade of service in terms of blocking and dropping probabilities and time taken to perform handover for a range of latitudes and a range of traffic intensities.

A.2. Model Employed

A.2.1. Satellite Constellation

For the simulation of carrier assignment performance a specific network configuration has to be assumed. Which orbit is chosen is unimportant for exercising the channel assignment algorithms as long as the orbit is non-GEO. A 769km altitude LEO is used for this channel assignment simulation since it represents an extreme case in that the relative motion between satellites and mobile terminals is fast, resulting in a lot of handover activity. The results obtained are also valid for MEOs at higher altitudes, the only difference being that the mean time between handovers will be longer, corresponding to the slower orbital velocity.

Figure 18(a) in chapter 4 shows the 7-beam per satellite pattern that is used, each beam being circular on the ground, having equal areas of 2,500,000km^2. Figure 15 in chapter 4 shows the 66 satellite constellation using 11 satellites[1] equi-spaced in each orbit, an arrangement similar to the new Iridium constellation but using only 7 beams per satellite, instead of 48 on Iridium satellites, and slightly different orbits. The six polar orbits are spaced with right ascensions 32° apart so that the beam patterns just provide complete coverage over the equator, as shown in figure 39. One or more satellites are always visible with elevations of 6.3° or more above the horizon.

Figures 40 and 41 show the simulation beam pattern at 30°North and 60°North, respectively, where the satellite orbits are converging. Simulations were performed for these latitudes and 0°North, which represent a range of latitudes rather than any worst cases. For simplicity, during the simulation all the beam centres are assumed to move due north at 6664m/s as one pattern, so the patterns have regular sub-satellite point spacing[2] to ensure that the beam spacing remains correct at the latitude of the observed area (exactly 0°North, 30°North or 60°North). In reality, these patterns would move on headings of 4°, 3.5° and 2°True respectively, but this direction is not significant for the simulation.

The software actually simulates the motion of the beam centres travelling due north at 6,664m/s by moving all the mobile terminals due south at that speed. Whenever mobile terminals leave the southern edge of the mobility area they are wrapped around to the northern edge of the mobility area by moving them 6,800km due north.

A.2.2. Traffic Model

An exponential distribution is used to model call duration and the time between call requests (i.e. the call request process follows a Poisson distribution, simulating completely random call requests). The mean call duration is kept constant at 105.6 seconds. The mean call rate is varied to provide traffic intensities that vary in terms of targets of mean calls in progress within the mobility area at any time from 100 calls to 500 calls, assuming that all calls would be set up and finish successfully.

Mobile terminals are "created" whenever a call is requested on the offered traffic schedule. The initial position of each mobile terminal is random but within a mobility area, which is within the simulation area. The distribution of terminals within the mobility area is uniform. The motion of mobile terminals, even on the fastest of aircraft,

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[1] Using this orbit it is possible to maintain complete coverage using only ten satellites per orbit. Eleven satellites are used here to provide additional overlap of coverage of satellites in the same orbital plane, facilitating handovers, and to allow more deviation in the station-keeping of satellite positions in their orbits.

[2] Note that the areas covered are so large that the top satellite of figure 39 is over 30°North and the top satellite in figure 40 is more than 60°North, so to show sub-satellite spacing over the coverage areas correctly, the satellite longitudes should be closer together at the tops of figures 40 and 41 than at the bottoms. However, since the continental outlines are for indication of scale only, this is not done: the satellite spacing all over the figure is the same so that they will be correct at the latitude of the relatively small observed area just by shifting the entire beam pattern up or down.

is insignificant compared with the motion of the satellite beam pattern, so mobile terminals are assumed to be stationary for the duration of a call.

A.2.3. Propagation Model

C/I ratios and received power levels are continuously re-calculated according to a propagation model to account for satellite motions and the changing communications traffic.

A.2.3.1. Satellite Antenna Pattern

The simulation area is completely flat and is covered by a maximum of 91 circular spot beams. The seven 1785km diameter circular spot beams shown in figure 18(a) are formed by each satellite using an "isoflux" antenna that has a gain pattern that compensates for the variations in path losses across the satellite footprint. The performance of this antenna is assumed to be ideal, so the path loss × antenna gain pattern is the same in all seven beams.

Initially, the classic parabolic gain pattern was used, given in dB by the equation

$$G(\theta) = G_m - 3\left(\theta/\theta_b\right)^2$$

where:

- $G(\theta)$ is the gain at angle θ from the beam centre ($\theta < 2.9\theta_b$);
- G_m is the maximum gain = 0.0dB;
- θ_b is the angle of the beam edge from the beam centre, i.e. 49° using "flat earth" geometry.

As the simulation model is of a flat, 2-dimensional space, θ is obtained from the distance from boresight, r, using $r = 769 \times \tan(\theta)$ km. The resulting "propagation model" is that shown by the thin dotted line in figure A1. The beam is so wide that the pattern's skirt projects above the satellite's horizon but interference is assumed to be negligible if the satellite is below the mobile terminal's horizon, i.e. the sub-satellite point is more than 2985km from the mobile terminal. This is a very simple model for a single feed circular nadir beam [REC672]. The initial verification tests of the simulation model proved that as a vehicle for evaluating handover mechanisms for satellites the antenna pattern proved to be insufficiently realistic, since there was excessive interference even thousands of kilometres away from the beam's nominal -3dB coverage.

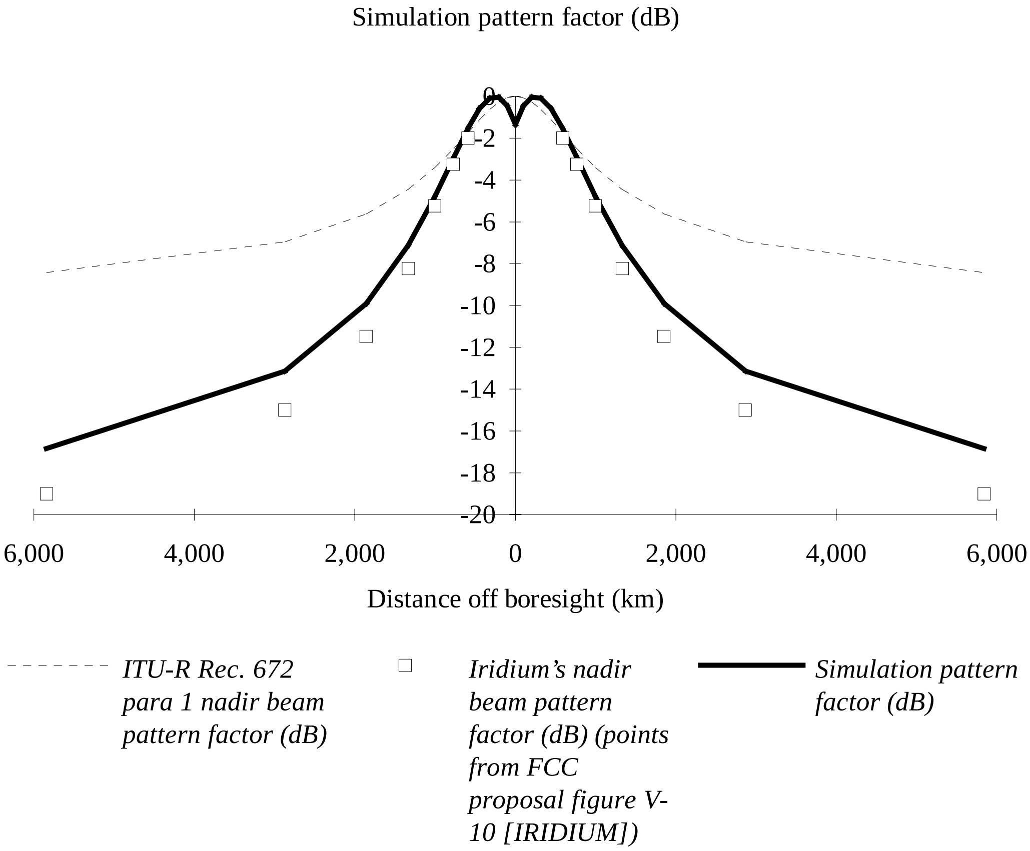

Figure A1 Antenna gain as a function of distance from beam centre, normalized to 0dB at the beam centre

The proposal in [IRIDIUM] shows better defeating of the out-of-coverage interference, presumably by using a larger effective antenna area to steepen the roll-off and multiple feeds for each beam to construct a wider plateau for the nominal coverage area. To calculate the pattern factor of a multiple feed beam the individual patterns of each feed must be added together (in phase as well as in magnitude) to give the combined effect. Since a simpler mathematical model of such multi-feed patterns was not available, it was decided to abandon a mathematically derived model in favour of a simple model that is as close as possible to the pattern factor of Iridium satellites' central beams. Since anything other than a parabolic shaped roll-off at the beam edge is a physical impossibility, this was preserved and the simulation model used is

$$G(\theta) = G_m - 3 \times \left(\frac{|\theta| - \theta_b/e}{\theta_b/{}^2\!/_3 e} \right)^2$$

where all the parameters are as before and e is the natural logarithm base. This is effectively the pattern of a narrower beam on one side of the boresight and the side of a different narrow beam on the other, ignoring all the interaction between the multiple narrow beams making up the pattern. Using θ_b=47° this pattern closely maps to Iridium's claimed performance, outside the edge of beam contour. However, the simulation was programmed with θ_b=49°, derived using a "flat-earth" model, and this was the pattern used as shown in figure A1. It is not as good as Iridium's claimed performance but it is much better than the ITU-R Recommendation 672 pattern and was deemed to be suitable for the simulation. The discontinuity at -1.3dB at the boresight is not a problem for the simulation software, as much larger discontinuities would result from shadowing effects in reality. Using this model, the edge of beam is a $(-3 \times ({}^{2}/_{3}(e - 1))^{2}) = -3.9$dB contour.

A.2.3.2. Shadowing, Fading and Thermal Noise

Because multipath fading occurs too rapidly for power control to follow the fast fades, power control is not used to compensate for multipath fading, only to compensate for shadowing effects. Rayleigh fading is not simulated, since it does not alter the thresholds at which handover becomes necessary or a call has to be dropped, which are defined by the C/I and received power when full transmit power is being used. A log-normal distribution could justifiably be used to simulate shadowing effects. Without empirical measurements of the effect using LEO satellites, the terrestrial model (which corresponds to a LEO satellite's worst case, just above the horizon) would be used. The fades for signals to and from all beams on the same satellite to any given mobile terminal should all be the same at any given instant because the radio paths are identical apart from the satellite antennas, which are assumed to be co-located.

Because of the tight time scale for this simulation the effects of shadowing on the channel assignment schemes were not studied.

Unlike terrestrial cellular systems, in the satellite environment thermal noise is significant. The C/I ratios described are really C/(I + N) ratios, where N is the thermal noise in the signal bandwidth. In this simulation we reference all powers to the maximum C received anywhere in any beam without any fading or shadowing. From section 2.5 we can derive $N_0 = -21\text{dBHz}^{-1}$ for the LEO satellite, compared with $N_0 = -77\text{dBHz}^{-1}$ for terrestrial cellular (no fading, both at the edge of coverage). To determine $N = N_0 \times$ (IF bandwidth) we need to know the IF signal bandwidth at the demodulator input, which has not yet been determined for any FPLMTS and may differ between terrestrial cell sites and satellites. To avoid making rash assumptions at this early stage, this simulation uses N = -90dB, which is negligible thermal noise. This low figure will increase the apparent capacity of the simulated system but comparison with terrestrial systems is not an issue in this simulation, so this imprecision is not important.

A.2.3.3. Thresholds Used in the Simulation

The channel assignment algorithms use both C/I ratio and received power thresholds, which are closely related to the propagation model and expected thermal noise. The values used are shown in table A1 and were selected during the verification testing of the model.

Ideally, these thresholds would be modified according to the utilization of the FES, thereby dynamically re configuring apparent beam radii to better cater for non-uniform offered traffic. This "fuzzy" algorithm was not used in the simulation because the simulation used a uniform geographic distribution of traffic. Even so, a fuzzy algorithm might have made better choices of the threshold values than those shown in Table A1.

	C/I Ratio (dB)	**Received Power (dB)***
Guaranteed minimum when a channel is assignd	+19dB (C/I_{block})	-4.0dB ($power_{block}$)
Minimum below which handover should be attempted	+16dB ($C/I_{try\ handover}$)	-4.1dB ($power_{try\ handover}$)
Minimum possible level for communications to still be possible	+13dB (C/I_{min})	-12.0dB ($power_{min}$)

* Unit of power is dB with respect to the maximum received power anywhere in any beam without any fade or shadowing. These power thresholds are therefore directly comparable to the (antenna gain × path loss) values shown in figure A1.

Table A1 Thresholds used in channel assignment

A.2.4. Network Sizing and FES Restrictions

The satellite network is sized assuming a total of 1MHz uplink and 1MHz downlink bandwidth to be shared world-wide (note that this is only $^1/_{30}$ of the bandwidth assigned to FPLMTS MSS at WARC '92). It is assumed that using about 10kHz bandwidth per carrier, approximately 100 carriers would be available, which is a manageable number of carriers for a simulation program to handle. Both the simulated DCA scheme and the fixed cell re-use scheme that it is compared with therefore assume a pool of 100 channels.

The simulation software is written as if each satellite has its own FES and is used exclusively by it. Each FES is endowed with 100 receive/transmit chains that are switchable between all spot beams on the satellite using a digital beam forming network. This permits the flexibility to handle unbalanced traffic demand where at any given time some spot beams cover more traffic than others. It also facilitates intra-satellite handover by allowing the spot beam to be switched whilst retaining use of the same receive/transmit chain. In addition, each satellite is restricted to using each channel in only one of its beams. This restriction stems from an assumption that the backhaul link between the satellite and FES would have the same bandwidth as the satellite to mobile terminals link and that this bandwidth would need to be shared between all the satellite's spot beams. The question of how each channel is switched between spot beams at the satellite is not considered here but it is believed to be simpler to switch individual Traffic Channels between spot beams than to switch individual carriers between frequencies or time slots on board satellites.

The software assumes nothing that would preclude the use of the same algorithms for a many to many mapping of spot beam to FES. The one to one mapping of backhaul link Traffic Channel to spot beam is entirely consistent with multiple FESs sharing the same satellite by sharing the same backhaul link.

A.2.5. Observation of Results

The simulation proceeds in steps each of a maximum of 2 second duration until a total of one million calls have been requested from the simulation area.

In the centre of the simulation area is the observed area, covering only the seven beams of the central satellite. Only calls from within the observed area are recorded for analysis to avoid recording abnormal effects at the simulation area's artificial edge. Within the observed area, the total number of call requests, call blockings, intra-satellite handovers, inter-satellite handovers, dropped calls, Paging Channel messages, Access Channel messages and deferred handovers are recorded. A log of the simulation records the following statistics:

A) simulation time (s);
B) mean number of calls in progress;
C) frequency of inter-satellite handovers (s between inter-satellite handovers);
D) frequency of intra-satellite/inter-satellite handovers (s between any type of handover);
E) probability of a new call being blocked (%);
F) probability of an existing call being dropped (%);
G) mean number of mobile channel measurements per inter-FES handover;
H) mean number of paging channels searched through by mobile per inter-FES handover;
I) mean channel interruption at inter-FES handover (s);
J) mean number of mobile channel measurements per intra-satellite handover;
K) mean channel interruption at intra-satellite handover (s);
L) maximum number of mobile channel measurements in one inter-FES handover;
M) maximum number of paging channels searched through by mobile in any one inter-FES handover;
N) maximum channel interruption in any one inter-FES handover (s);
O) maximum number of mobile channel measurements in any one intra-satellite handover;
P) maximum channel interruption in any one intra-satellite handover (s);
Q) probability of call continuing with a poor channel (%);
R) mean duration of poor channel condition (s).

A.3. Simulation Results

Simulations were made of DCA using 5 retry and 20 retry ceilings on the number of channels tested on a satellite. Each scheme was trialled at 0°, 30° and 60°North with call schedules of 100, 200, 300, 400 and 500 "mean requested calls in progress within mobility area". This unit of traffic intensity is the mean number of calls that would be in progress within the mobility area *if all call requests were successful and all calls continued through to normal completion*, i.e. no calls are blocked or dropped. The mean duration of a call is 105.6s, the mean duration of calls on Japan's analogue cellular networks.

A.3.1. Dynamic Channel Assignment

A full description of the results obtained by simulation is presented in appendices B and C. Appendix B contains results for the single channel receiver (5 retry) scheme and appendix C contains results for the dual channel receiver (20 retry) scheme. A comparison of the two shows that there is no advantage to be gained by increasing the number of channels that can be tested by the mobile terminal and that doing so is counterproductive. This seems at odds with intuition but the arguments presented in chapter 7 explain this. These simulations indicate that there is an optimum number of retries that should be allowed on a system and that for this model it is closer to 5 retries than it is to 20 retries.

The simulations confirm that the major bottleneck in the simulated handover process is the mobile terminal searching for a new satellite to communicate with after its old FES has signalled that it is unable to find a spare channel on the same satellite as before. It is proven that if a FES were able to communicate through multiple satellites then the FES would be able to assign a spare channel on a new satellite itself rather than leaving the mobile terminal to find a new satellite. This would shorten the time necessary to perform inter-satellite handovers.

The simulation reported in appendix B allowed a mobile terminal to request a communications channel to five different satellites before the call was blocked. The simulation reported in appendix C allowed requests to be made to up to 20 different satellites. A comparison of the blocking probabilities for these two simulations shows a clear advantage in allowing the larger number of requests to be made. As this only increases the call set-up time (rather than handover time) and the blocking probability remains higher than the dropping probabilities, the larger limit on requests is recommended for use in any DCA scheme.

The results show the capacity of the simulated system to be approximately 4.3 channels/1,000,000km^2 for a 100 channel pool, producing satisfactory blocking and dropping probabilities. This network capacity is compared with the fixed cell re-use plan in the next section.

A.3.2. Comparison with a Fixed Frequency Re-Use Plan

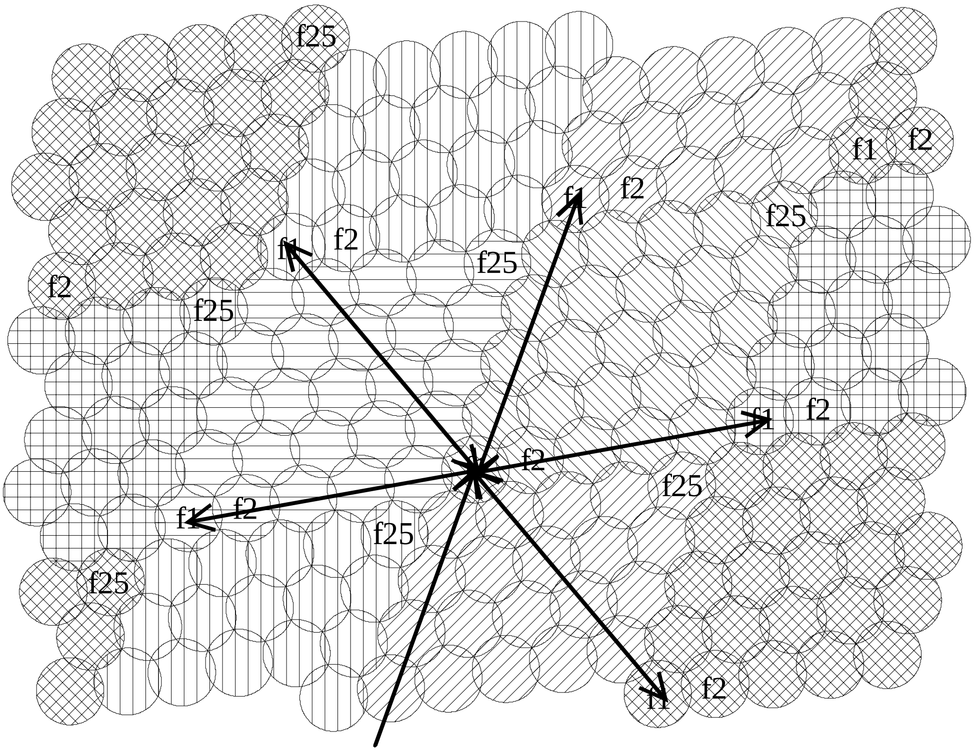

Figure A2 25 cell diamond-shaped frequency re-use pattern showing 7730km frequency re-use distance

A fixed frequency reuse plan is created from patterns that repeat at distances greater than the minimum frequency reuse distance. Minimum frequency reuse distance is determined from the minimum acceptable C/I level and the propagation model. To draw a fair comparison with the simulated DCA model the minimum frequency reuse distance must be derived from C/I_{block} (+19dB), the guaranteed minimum C/I whenever a channel is assigned. The cell pattern chosen is a hexagonal pattern, so a mobile terminal may encounter interference from the six nearest cells that reuse its frequency. Therefore interference from any one cell into another where the same frequencies are reused must be kept below $-(10\times\log(6\times10^{19/10})) = -27$dB with respect to normalized carrier power. Using the simulation model of antenna pattern factor it is found that power does not drop to below this level until the satellite is beyond the horizon of the mobile terminal, no matter which beam of the satellite is being used[3]. As in the simulation, negligible thermal noise is assumed. The minimum frequency reuse distance is therefore specified as the diameter of the 0° elevation contour for the satellite, 5970km.

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[3] Note that frequency reuse between beams on the same satellite would be impossible anyway because of the way it has been assumed that feeder link spectrum is divided between beams by the digital beam forming network.

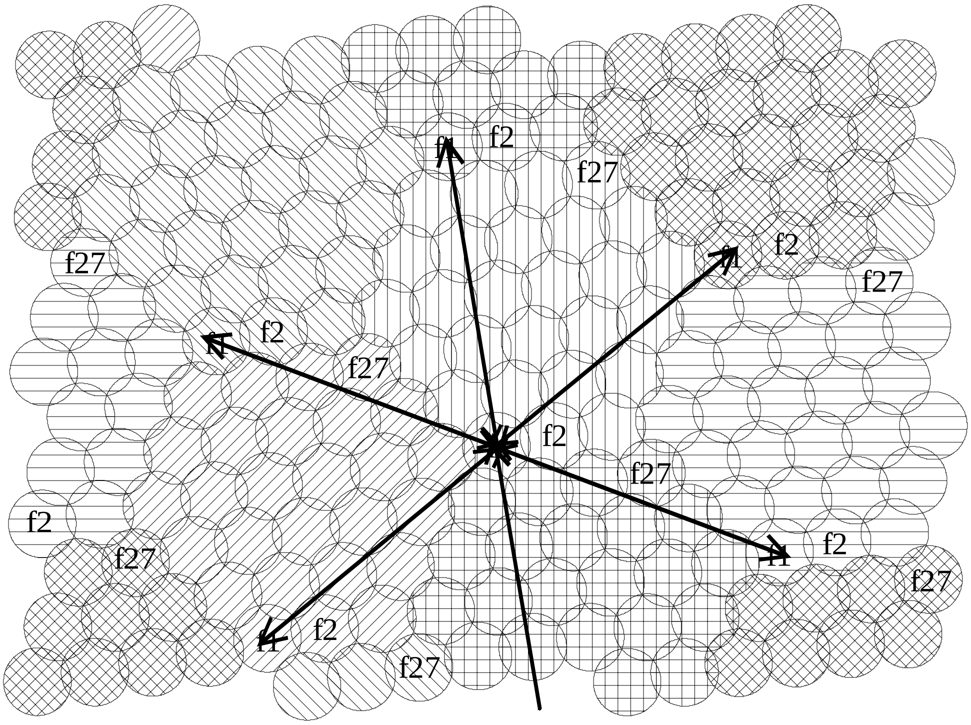

Figure A3 27 cell hexagonal frequency re-use pattern showing 8035km frequency re-use distance

The cell diameter was chosen to be the same as the diameter of a satellite spot beam. Note, however, that cells and spot beams are different things. Cells are areas fixed on the Earth's surface to which channels are permanently assigned. Spot beams will move over the cells, adopting the cells' channel assignments as they pick up the cells' traffic. Alternatively, spot beams could be steered to track the cells, it makes little difference to the system capacity. To translate the minimum frequency reuse distance into the minimum distance between cell centres the radius of a cell, 1785km, must be added totalling 7755km. The closest match to this figure is obtainable using a diamond-shaped 25 cell tessellation pattern with a distance between beam centres of cells reusing frequencies of 7730km, shown in figure A2. This pattern is fixed on the Earth's surface and shows where the frequency block f1 may be reused. Areas shaded in the same hatch use different frequency blocks (f1 to f25) and it can be seen how this pattern repeats across the surface of the Earth. The next size up is thought to be more suitable, a hexagonal 27 cell pattern with inter-reuse cell centres spaced 8035km apart shown in figure A3. Satellite coverages move independently across these geographically fixed cellular patterns. The 27 cell reuse pattern represents poor frequency reuse compared with the 7 cell reuse patterns that have been proposed for some systems and this is a reflection of the poor out-of-beam defeating of signal power from the modelled antenna and the high C/I requirements that were specified. Since the DCA algorithm was simulated using the same model the comparison of fixed frequency re-use planning with DCA is valid using this model.

The area of each hexagon that represents each cell in the pattern is 2,071,000km^2. Thus the capacity of the fixed 27 cell reuse plan is (100/27/2.071) = 1.79 channels/1,000,000km^2 for a 100 channel pool. Thus the DCA scheme is shown to increase capacity by a factor of 2.4.

A.3.3. Limitations of Simulation Model

The effect of Doppler frequency shift on Traffic Channel carriers was not simulated and would have resulted in the forcing of more handovers as interference was introduced by Traffic Channels converging due to Doppler frequency shifts. The simulation used a very basic algorithm to attempt to keep Traffic Channels used on a satellite in a continuous block in the frequency spectrum. Using an interactive debugging shell to the simulation and CodeView, this algorithm could be seen to be not particularly successful at preventing fragmentation of the block. This algorithm should be improved before this particular scheme or the effects of Doppler shift are studied any further.

Shadowing, which should have been a major consideration, was not simulated either, due to a lack of time. Shadowing will be particularly bad for satellites using very low link margins. Diversity, the ability of mobile terminals to dynamically select any satellite that is above the local horizonn, will help to relieve the adverse effects of shadowing as mobile terminals hand over to satellites for which shadowing is not so severe. Thus shadowing would also force more handovers than were observed in this simulation but should increase the dropped call probability only very slightly. However, shadowing resulting in rapid reductions of received power of 8dB or more might require a re-think of the threshold levels that were used in this simulation or a means of significantly speeding up handover completion when received power drops rapidly (see section 6.5.4). Ideally, a "fuzzy" system of dynamic thresholds should be implemented.

Finally, the simulation assumed only one FES using each satellite and each FES using only one satellite. This is not the case in reality as FESs are likely to be located on the ground and will have to swap between satellites as they pass by just as mobile terminals do. The conclusions from the thesis recommend the use of multiple satellites by each FES to improve inter-satellite handover performance and the algorithms' structures will need to be altered to enable the simulation of many-to-many mapping of FESs to satellites, rather than the one-to-one relationship it reflects at the moment.

A.4. Summary of Results

The capacity of a satellite system is low compared to a terrestrial system with the same number of cells and the same size of channel pool, primarily because satellite antenna pattern roll-offs are not as steep as the r^{-4} or even the r^{-2} roll-off curves used to model terrestrial systems. Frequency re-use distances must consequently be larger to avoid the greater out-of-beam interference. The capacity could be improved by using larger antennas to attenuate out-of-beam interference more but a simple antenna pattern is sufficient to allow comparison between the fixed re-use plan and DCA schemes.

DCA was shown to provide a 2.4-fold increase in system capacity over the fixed reuse plan in return for a little added complexity at mobile terminals. Handover using DCA is slower than using fixed re-use plans, though a dual channel mobile receiver would hide this fact from the customer. For optimum performance the FES should not distinguish between dual channel receivers and single channel receivers but offer the same numbers of Traffic Channel proposals to each type, limiting the number to around five retries. In this case, the mean time taken to complete an intra-satellite handover would be less than one second, which could be an acceptable call drop-out for customers using low cost single channel mobile receivers.

It is recommended that FESs be enabled to communicate with mobile terminals through a number of different satellites simultaneously, such that an FES can hand a mobile terminal over from one satellite to another without losing control of the channel assignment process. This ensures that the interruption at inter-satellite handover does not rise much above the interruption at intra-satellite handover.

Finally, it appears that more time be invested in initially searching for a satellite with a free Traffic Channel than is spent searching for a new Traffic Channel for handover once a call is in progress. With conservative choices of C/I and minimum power thresholds the call dropping probabilities were made to be low at 0.8% and the probability of a call suffering from poor channel quality during a call was made an order of magnitude smaller than this. The limits on search times to set up a new call can be made large enough to achieve a similarly low call blocking probability.