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AUTOCELL An Intelligent Cellular Mobile Network Management System

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■ AUTOCELL is a system developed to assist in the operation and management of cellular mobile networks operated by Singapore Telecom. Its deployment is in line with the company's strategic move to introduce intelligent software into its operations. With the help of AI concepts and techniques, the system has enhanced the operational efficiency and network capacity and increased customer satisfaction with the network.

The use of mobile phones in Singapore has been increasing rapidly since they were introduced by Singapore Telecom (ST) in 1988. To meet this ever-rising demand and maintain high-quality service, ST has to continually expand and improve the cellular networks that it operates.

AUTOCELL is an intelligent operations management system that allows ST to better manage the AMPS and ETACS cellular networks with the provision of online monitoring, planning, and control facilities. The system was jointly developed by ST and the Information Technology Institute (ITI), the applied research and development arm of the National Computer Board. The AUTOCELL system for the AMPS network was deployed in October 1994, and work on porting the system to the ETACS network has been completed; the system was deployed in October 1995.

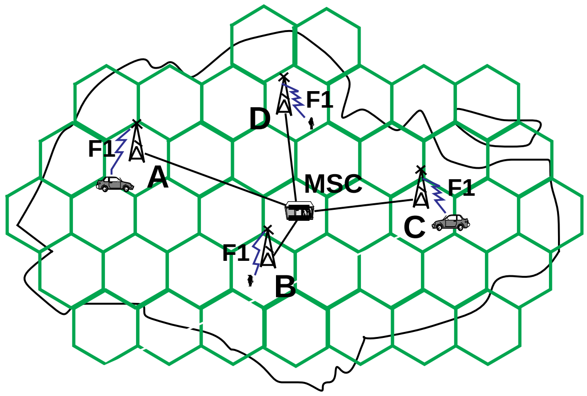
In this article, we describe how the integration and synergy of data, human expertise, and computer technology has generated value for ST. In particular, we focus on how and where AI concepts and techniques have proven valuable in this endeavor.

Background on Cellular Communications

A cellular mobile network (figure 1) divides the service area into a number of cells, each of which offers a set of voice channels to carry calls to and from mobile phone users in the cell's coverage area. Each cell contains a base station where the transceiver hardware for voice channels is installed. The base stations are linked by line circuits to a central control unit called the *mobile switching center* (*MSC*), which performs various control and administrative functions, such as the activation of voice channels and the reporting of network alarms and traffic data.

Each call to and from a mobile phone takes place over radio waves, at the preset frequency of a voice channel, between the mobile phone and the base station of the cell. The number of concurrent mobile calls that can be supported in any one cell is therefore constrained by the number of voice channels available in the cell. Each voice channel is associated with a specific frequency channel taken from the frequency band allocated to ST. Because the total number of frequencies available in the band is limited, the frequencies are a scarce resource that must be used efficiently.

Cellular networks achieve efficient use of the allocated frequencies by allowing the same set of frequencies to be reused at several nonadjacent cells. This arrangement allows calls to be carried by voice channels of the same frequency at several places in the net-



Hypothetical cellular network over the island of Singapore — Here, frequency F1 is re-used in cells A, B, C and D. This allows 4 concurrent calls carried by F1 to take place simultaneously, assuming that there is no *co-channel interference* between any pair among the 4 cells.

Figure 1. Frequency Reuse in a Cellular Network.

work at the same time, thereby increasing the effective call-handling capacity. Figure 1 illustrates a frequency F1 that is reused at four separate cells in the network. Such a group of cells is called a *cell group*.

Although the coverage of the cells is presented as nonoverlapping hexagons in figure 1, in reality, the coverage areas are irregularly shaped and overlapping because of the irregularities of terrain and radio-wave propagation. As a result, the coverage of any one cell will overlap with that of another. Should the same frequency be used simultaneously in these cells, interference would occur, resulting in cross talk or dropped calls. This phenomenon is called *co-channel interference*. To avoid co-channel interference, the network staff must ensure that the same frequency is not in use at any two mutually interfering cells over the same time period. This process involves *blocking* (that is, disabling) the frequency channel in one cell so that it can be used freely in the other. The act of changing the availability of a frequency channel among cells by blocking it in one cell and unblocking it in another is called *frequency reassignment*.

A well-managed cellular network is one that has no interference, a high use of base station equipment, and a *good grade of service (GOS)* in all its cells. The GOS represents the probability of a call attempt being blocked. Therefore, a congested cell will have a poor GOS, which is manifested in the form of a high number of failed call attempts and dropped calls. Typically, a GOS of 2 percent or less is considered desirable, and a GOS above 5 percent is considered unacceptable.

Problem Description

Because of the increasing number of cellular mobile subscribers, changes in physical terrain (for example, because of new buildings and highways) and changes in demographic profile in various areas (for example, because of new housing estates), ST must continually monitor the performance of the network to detect performance deficiencies (for example, interference between cells or a shortfall of available channels at a cell). Such deficiencies can then be addressed through various means such as adjusting the coverage of cells (that is, adjusting the base station antenna), splitting cells, adding new cells, and installing additional channels at existing cells. This task of monitoring for and remedying network deficiencies is performed by a team of network planners, field engineers, and operations and management staff members. The operations and management staff is responsible for acquiring and collecting various traffic and network status data from the MSC. The field engineers will conduct field measurements to detect intercell interference. The network planners will then analyze the data provided by team members and work out the appropriate near-term and long-term solutions to improving network performance.

The work flow prior to the introduction of AUTOCELL suffered from three major drawbacks: First, the acquisition of network and traffic data was a tedious and labor-intensive task. The operations and management staff had to interface with the MSC through a command-line interface that accepted mnemonic commands and output raw data in a fairly cryptic format. Typically, an experienced staff member would devote one person-day to collect a few days' worth of data and generate reports with the help of a spreadsheet tool. Because of the time and effort required for this task, the operations and management staff would typically only generate such reports on a few selected days each month.

Second, as the cellular network expanded and evolved, the network planners were finding it increasingly difficult to cope with the sheer number of network elements (cells, channels, and so on) involved. Because network data were not captured regularly or were not available online, the planners were unable to perform any extensive or computer-intensive studies based on past network behavior, such as computing the required

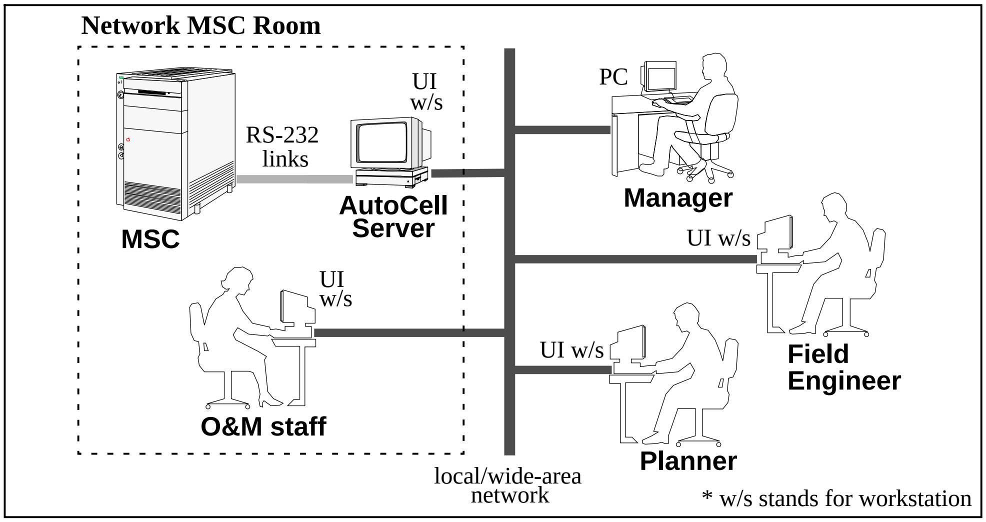


Figure 2. The AUTOCELL System Overview.

channel capacity of each cell over the past few months under various performance targets (say, 2-percent or 5-percent GOS). This inability in turn hampered their long-term network planning efforts.

Third, because of the frequent fluctuations in network and traffic conditions, it was laborious for the operations and management staff members and the planners to monitor each and every network element closely. It was difficult for them to quickly invoke corrective action to alleviate abnormally high traffic congestion in some cells or temporary network performance deficiencies as a result of such causes as faulty equipment.

Objectives of AUTOCELL

The AUTOCELL Project was initiated with three main objectives: The first objective was to provide easy access to useful past and present information about the network. This access was to be achieved by automatically acquiring network and traffic data from the MSC; storing the data in the database; and presenting value-added information, through a user-friendly graphic user interface, to the operations and management staff members, planners, field engineers, and managers.

The second objective was to provide assistance and recommendations to network planners in monitoring and improving overall network performance. AUTOCELL was to apply frequency planning expertise on the database of historical network data to assist the planners in deriving actions that would improve the performance of the network.

The third objective was to perform automatic frequency reassignment to alleviate temporary network congestion. AUTOCELL was to dynamically track the network status and traffic conditions at various cells throughout the day and automatically reassign channels from less congested cells to more congested cells.

AUTOCELL System Overview

AUTOCELL is a distributed client-server system composed of the AUTOCELL server that runs round the clock on one workstation and of user interface clients running on several (possibly remote) workstations (figure 2).

The AUTOCELL server is connected by RS-232 links to the MSC, from which it periodically acquires network status and traffic data. The collected data are processed and stored in a central database. At regular intervals, the server will generate traffic forecasts for all cells and perform automatic frequency reassignment to make more channels available (if possible) at cells that are congested because of unexpected high demands or faulty channels. The server will also accept requests from any of the user interface clients to generate traffic forecasts and optimize frequency assignments for some future time period.

The AUTOCELL user interface provides the network operations and management staff with a user-friendly interface for monitoring the current status and traffic conditions of the network. The user interface panels include maps, graphs, and tables that are color coded to quickly draw the attention of operational staff members to abnormal conditions. These panels refresh automatically

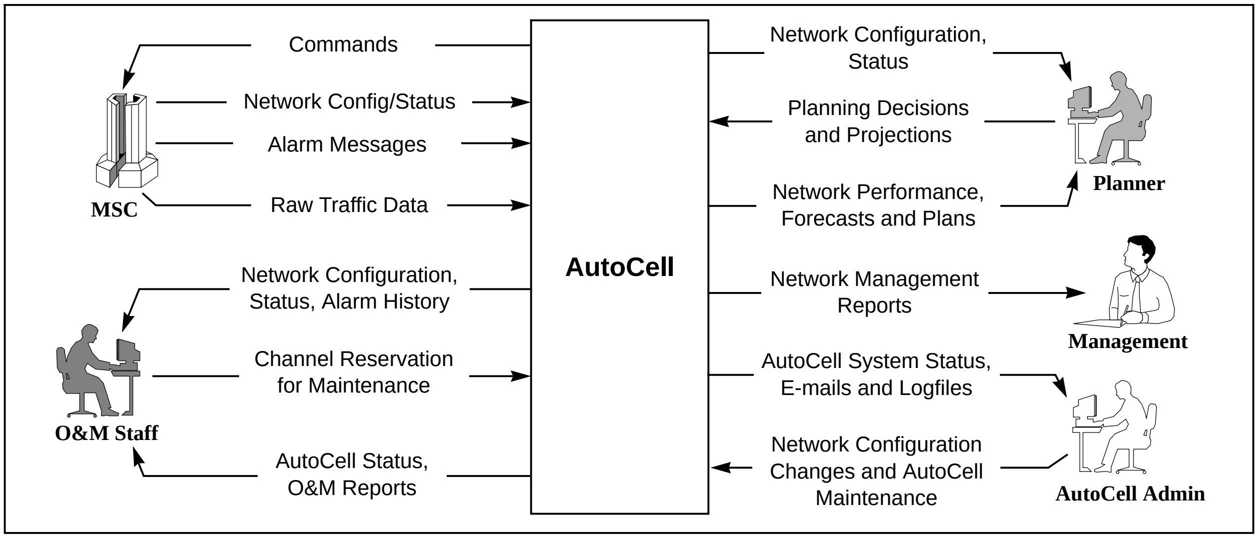


Figure 3. AUTOCELL *Information Flow.*

whenever new traffic or status data become available.

The AUTOCELL user interface also provides network planners with an intuitive interface for network analysis and planning, including panels that allow one to review past and present traffic-demand graphs and evaluate the impact of adding and removing channels to and from one or more cells. More importantly, the user interface workstation can be run from the planner's own desktop, allowing him or her instant access to information about the network.

AUTOCELL also provides a reporting facility where regular or ad hoc reports on traffic demand and network performance can be generated on screen or printed out. This report module can be invoked from any workstation or PC that has access to the AUTOCELL database.

The overall data and information flow of the AUTOCELL work environment is illustrated in figure 3, and sample screen panels of the user interface are shown in figure 4.

Technical Challenges

The team identified three aspects of AUTOCELL that were technically challenging. We elaborate these challenges in the following subsections.

Interfacing with the MSC

The MSC provides a set of serial ports from which traffic data and alarm messages can be output autonomously, and from which commands that are issued by AUTOCELL to query for status or configuration data or to invoke changes in the network can be accepted. However, the MSC can only process one command at a time, and the time taken for the reply can vary from 10 seconds to 30 minutes depending on the command type, the parameters, and the current processing load of the MSC. Furthermore, sending too many commands to the MSC can potentially affect its processing throughput on its other (perhaps more important) tasks. Thus, AUTOCELL can only send commands sparingly to the MSC and still be able to maintain up-to-date status information and perform periodic channel reassignments.

A careful strategy must therefore be formulated so that commands are sent to the switch only when necessary. For example, a poll-channel-status command should be sent on a cell-down-alarm message. Commands can also be scheduled to be executed at appropriate intervals (for example, hourly or daily). Furthermore, should the MSC be late in delivering a reply to the current command, lower-priority commands due for execution should be dropped so as not to affect the timeliness of the more important commands. Such a strategy was formulated with the help of a few expert operations and management staff members who were able to provide much strategic expertise (when to do what) to go with the procedural knowledge (how to parse MSC data) that was gleaned from the MSC manuals.

The challenge for the AUTOCELL team was, therefore, to devise a suitable architecture where multiple data streams can be handled concurrently, time- and event-driven commands to the MSC can be sent, and procedu-

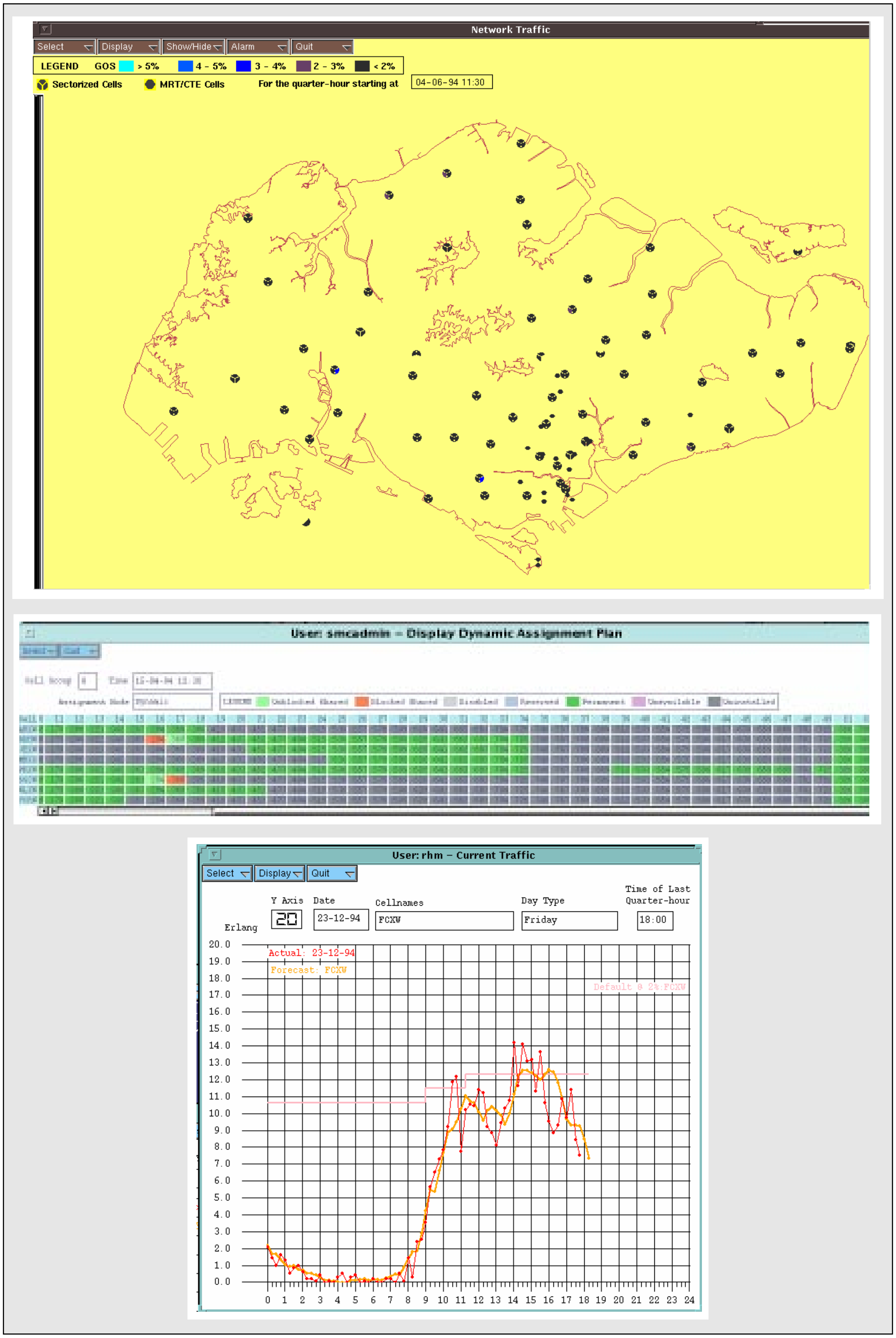


Figure 4. Sample Screen Panels of the AUTOCELL *User Interface.*

A. Network Grade of Service.
B. Dynamic Frequency Assignment Plan.
C. Cell Actual, Forecasted, and Supported Traffic.

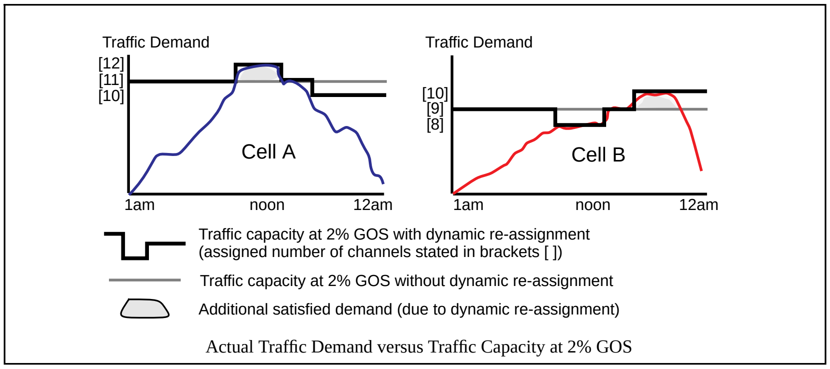


Figure 5. Dynamic Reassignment between Two Interfering Cells.

ral and strategic knowledge can be encoded in a modular fashion. In particular, this architecture must facilitate the evolution of AUTOCELL to handle additional data streams, additional traffic data types, or changes to the MSC's processing capabilities.

Network Analysis and Planning

The network planners have observed that recurring traffic-demand patterns exist at various cells at various hours of a day over various days of a week. In other words, the traffic demand at a cell for a particular day, say a Tuesday, will not vary significantly from that of the few Tuesdays immediately before or after it. Such traffic patterns, if computed, succinctly represent the expected traffic demand at each cell and facilitate the planning for enough capacity to cater to the expected demands at each cell. Therefore, what the planners need is for AUTOCELL to automatically compute the traffic patterns for all cells using traffic data collected over the recent few months. However, no obvious formula exists for computing a traffic pattern based on past traffic-demand samples. Hence, an algorithm needs to be developed that makes use of the expertise of the experts, in particular, how to weigh traffic data samples of different recency; how to judge whether a generated pattern is representative of samples that it is generated from; and how to detect and handle data samples that are incomplete, erroneous, or abnormal.

Dynamic Frequency Reassignment

The network planners also observed that the shape of the traffic-demand curve of a given day does vary with different cells. For example, the traffic demand at a cell in the urban area might peak at noon, but the demand of another cell in the suburban area might peak in the evening. This phenomenon gives rise to the opportunity of sharing the same frequency at any two or more mutually interfering cells that peak at different hours by dynamically reassigning a frequency from one cell to another based on where the demand is higher (figure 5). This concept is called *dynamic frequency reassignment,* which is aptly described by Calhoun (1988): "This would allow the network to 'breathe' with the flow of traffic, shifting channels back and forth between cell sites as necessary, putting the spectrum resource where the need is greatest" (p. 258).

To be able to apply dynamic reassignment effectively, AUTOCELL must be able to accurately forecast the traffic demands at each cell for each time period (for example, quarter hour) and then be able to optimize the frequency assignments with respect to the expected demands and performance criteria of each cell. It must also minimize the number of channels to be reassigned to prevent overloading the MSC.

How AI Is Applied in AUTOCELL

In the earlier technical challenges, the team looked toward AI to provide the solutions. However, the team discovered that the nature of the human expertise acquired is broad but shallow and not particularly amenable for representation in any single AI representation. There are AI tools that address some of AUTOCELL's requirements, but the payoff from using each of these tools was deemed not commensurate with the costs and risks involved in procurement, training, integration, support, and maintenance. Therefore, the team and user management decided to adopt a more customized approach that would borrow heavily from existing AI concepts if appropriate and that would not preclude the future inclusion of AI tools should the need arise.

In the case of traffic-pattern and forecast generation, the team decided to adopt conventional statistical algorithms to perform the tasks. Human expertise is encoded either directly into the algorithms used or in the form of parameters that can be adjusted from the AUTOCELL user interface. In addition, because the team and the experts were unable to formalize a general strategy for predicting traffic demand resulting from special events (when a higher-than-expected demand in some cells is anticipated), some means are provided for the user to manually edit the forecasts to reflect the expected demand (if predictable) of these special events.

In the case of providing flexible event-driven control in AUTOCELL, as well as the optimization of frequency assignments, AI principles and techniques proved to be valuable. These principles and techniques are elaborated in the following subsections.

A Multiagent Event-Driven Architecture

Because AUTOCELL is required to handle multiple MSC data streams in an event-driven manner, it requires an architecture that allows concurrent processing of the MSC data and flexible control of processing activities that are triggered by various events. The team decided to adopt a multiagent event-driven architecture based on AI object-oriented techniques.

Each MSC port is handled by an agent program (running as an individual UNIX process), each of which specializes in handling the input-output with the specific MSC port (see subbox in figure 6). Within each agent program, expertise on how to parse and store the collected MSC data is encapsulated as separate objects in the program. As new data arrive from the MSC port, the appropriate object is invoked to parse and process (for example, store in database) the data items. Each agent also monitors its port for problems such as corrupted data or nonarrival of data.

All these agents are in turn controlled and monitored by a controller program called the *MSC interface controller.* This controller program communicates with the agents through an exchange of messages. The messages can be in the form of requests from the controller to an agent (for example, start-collecting-traffic) or notifications from an agent to the controller (for example, cell-down-alarm). Therefore, the controller program is where the strategy for interacting with the MSC can be implemented. We encoded the appropriate actions in response to different events within separate task classes, used a message-interpretation loop to map incoming messages to new or existing tasks, and maintained a task agenda to hold ready and pending task instances of various expiration times and priorities. For example, a cell-down-alarm notification from the MSC alarm agent to the controller invokes a handle-cell-down-event task in the controller. This task in turn sends a poll-channel-status request to the MSC command-reply agent. The command-reply agent then dispatches the appropriate MSC command to the MSC, collects the reply, and updates the status database.

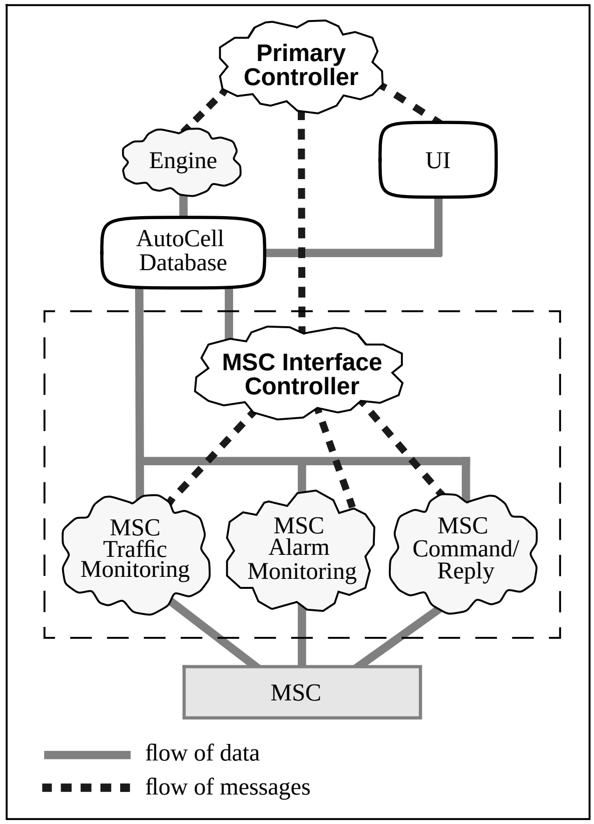
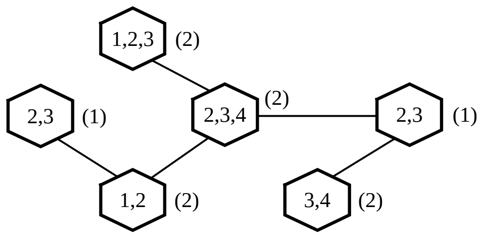


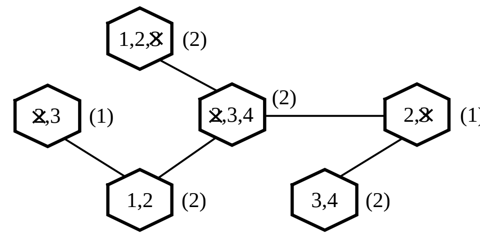
Figure 6. The AUTOCELL Multiagent Architecture.

This architectural scheme turns out to be useful beyond the scope of interfacing with the MSC and is, in fact, replicated at the highest level of the AUTOCELL server architecture (figure 6). In this case, an overall controller module called the *primary controller* communicates with its two agent programs: (1) the MSC interface controller described earlier and (2) an engine program that specializes in various value-adding data processing tasks (for example, derivation of traffic patterns, optimization of frequency assignments).

The role of the primary controller is to invoke various processing tasks in response to events. An event can be a preprogrammed notification based on time (for example, every Monday at 0130 hours), a notification because of some MSC event (for example, arrival of new traffic data), or a user request from one of the user interface clients (for example, to pregenerate optimized frequency assignments for some future time period). The primary controller is also responsible for reporting various events to all the active user interface clients (for example, arrival of traffic data) so that each user interface can refresh its respective panels.



Problem: To select frequencies to de-activate so that no 2 interfering cells (linked by edges above) have any activated frequencies in common and so as to minimize the worst-case shortfall in active channel supply wrt the expected demand (specified within brackets).



Solution: De-activate the frequencies that are crossed out. In this case, the minimum worst-case shortfall is zero.

Figure 7. A Hypothetical Frequency Assignment Optimization Problem and Solution.

This scheme allows one to schedule various processing activities in a way that maximizes the use of the AUTOCELL server, which, like the MSC, is a resource with processing throughput constraints. For example, heavy processing tasks, such as the generation of traffic patterns, can be scheduled for off-peak hours.

Central to the entire scheme is the AUTOCELL database that all controllers and agents have access to. The database allows one agent to work on top of information produced by another agent. For example, the MSC traffic-monitoring agent first records collected traffic-demand data into the database. The engine program then performs some additional error checking and computation on the data and later uses it to generate traffic-demand patterns and frequency assignment plans. The assignment plans are in turn read by the MSC interface controller to carry out channel reassignments.

The architecture also allows some form of fault tolerance to be built in. The primary controller, for example, continually monitors the state of its agent programs. Should any of them crash, the primary controller immediately restarts the crashed agent.

Heuristic Search

A *frequency assignment plan* assigns frequencies to be activated in each cell in a cell group for a specific time period. A feasible assignment plan must respect constraints imposed by the set of installed frequencies at each cell and the co-channel interference constraints between cells. In AUTOCELL, the frequency assignments must be regenerated every 15 minutes so that reassignments can take place every quarter hour.

The objective of the frequency assignment optimization is to find a set of feasible assignments to each cell that is optimal with respect to some specified criteria, for example, minimizing the shortfall in channels assigned with respect to the forecasted traffic demand at some target GOS. This objective represents a graph-coloring problem, as illustrated in figure 7, where the vertexes (hexagons) represent cells, colors (depicted as integers within each hexagon) represent frequencies installed at each cell, and edges represent co-channel interference relationships.

In addition, AUTOCELL's optimization algorithm should achieve a near-optimal solution under two minutes, always generate a feasible solution, and minimize perturbation from the current (or some default) channel assignments.

With these points in mind, a heuristic incremental refinement algorithm (Low 1994) was developed for AUTOCELL. The algorithm is a two-level search: The first level involves a steepest-ascent hill-climbing search that repeatedly seeks the most needy cell whose interferers can donate a frequency. The second level involves a simple search that uses a heuristic penalty-scoring scheme and branch-and-bound pruning to select the best frequency to be reassigned to the identified needy cell.

The basic goal of this algorithm is to continually seek to improve on the more needy cells by reassigning frequencies to them from less needy cells. Therefore, each successful iteration through the search improves the overall performance (predicted) of the cell group a little more until a local optimum or the given iteration limit is reached. In this way, the algorithm will always produce a solution that is no worse than the initial solution.

The various decision points in the search where heuristics can be applied are captured as decision functions. This approach allows the team to tweak the performance or the optimization criteria of the algorithm by modifying just the decision functions. For example, the functions currently implement the following set of criteria, listed in descending order of priority: (1) minimize the worst-case GOS of cells whose GOS is worse than 5 percent, (2) minimize the number of cells whose GOS is worse than 5 percent, (3) maximize the number of cells at or better than 2-percent GOS, and (4) prefer assignment plans that are aesthetically pleasing when displayed (that is, where blocked and unblocked channels are grouped into contiguous bands).

Development, Deployment, and Maintenance

In this section, we discuss the development schedule and the costs and resources associated with system development. The development and deployment plans, as well as the maintenance plan, are also presented.

Development Schedule, Costs, and Resources

A team of five developers (two from ITI, three from ST) took about two years to complete the AUTOCELL system on the AMPS network. The time spent included domain study, technical training, and hardware- and software-acquisition time. The total project cost, including hardware, software, training, and development, was estimated at about US$900,000. AUTOCELL is developed and deployed on a network of Sun SPARCSTATIONS running on SOLARIS 1. The AUTOCELL server is developed in C++ using the GNU suite of C++ tools. The AUTOCELL user interface is developed using the ILOG suite of user interface tools. The database is implemented on INFORMIX ONLINE.

Development and Deployment Plan

The development and deployment of AUTOCELL was broken into phases 1 (15 months) and 2 (9 months).

The aim of phase 1 was to develop a system that is able to interface with the MSC so that sufficient traffic data can be collected by the end of the phase for use in traffic analysis and forecasting and so that enough experience could be gained for use in deriving a reliable MSC control strategy. The team also spent time exploring various forecasting and optimization algorithms and was able to quickly implement a few user interface displays that allowed the users to visually inspect and comment on the quality of the generated traffic forecasts and assignment plans.

The team realized that the confidence of the users in the system cannot be assumed; hence, several manual checkpoints and overrides were implemented into AUTOCELL to assure the users that the system will not cause undue degradation to the network's operations. For example, the users were required to pregenerate and approve (using the user interface) each frequency assignment plan before any reassignments took place.

AUTOCELL was deployed at the end of phase 1 with the ability to capture traffic data; perform traffic-pattern generation; and perform preplanned frequency reassignment, with access to this capability given to a few selected users. This deployed phase-1 system would continue to operate while phase-2 development carried on. Within one month of deployment, the users had gained sufficient confidence in AUTOCELL to request that some of the manual controls be removed so that channel reassignment could be executed in a less supervised manner.

The aim of phase 2 was to further enhance the data capture, forecasting, and optimization capabilities of AUTOCELL and complete the user interface displays. In particular, the team focused on implementing dynamic forecasting and frequency reassignment every quarter hour to cope with unexpected traffic surges and down channels.

The full AUTOCELL system was deployed in October 1994 after the completion of phase-2 implementation, user training, and acceptance testing.

A new team was formed and trained to port the application to the ETACS network. This new project started in July 1994, and the system was deployed in October 1995. The implementation effort is estimated to be about 44 percent of that spent on the original system.

Maintenance Plan

The users are not expected to perform any software maintenance on AUTOCELL. However, network planners are allowed to tweak certain aspects of AUTOCELL's forecasting and optimization algorithms by adjusting certain global or cell-based parameters (for example, target GOS of a cell). However, new requirements and changes in control strategy are expected to be implemented by software engineers from ST. The maintenance effort will be facilitated by the modularity, the object orientation, and the separation of data processing logic from control logic in AUTOCELL's design.

Application Use and Payoff

AUTOCELL was deployed as a network-monitoring system in October 1993 and began performing automatic dynamic channel reassignment in March 1994. The benefits accrued to date from its deployment are described in the following subsections.

Increased Revenue

With the help of AUTOCELL-generated recommendations, ST has been able to identify and transfer 97 voice channels (with its associated hardware) from uncongested cells to cells that are congested or that are exhibiting rapid growth in demand. This assistance has helped increase the overall capacity of the network without requiring any purchase of additional hardware while maintaining the same level of service. ST estimates that the additional traffic demand carried to be worth about US$880,000 in revenue for the first year alone. Such reconfiguration exercises are expected to be conducted on a regular basis with the help of AUTOCELL.

Since March 1994, AUTOCELL has been applying dynamic channel reassignment to a pilot group of eight cells. The monthly gains in traffic revenue have varied between US$350 and US$1400 a month for these eight cells alone. The gains are expected to become more substantial as further demand and subscription growth strain the capacity of individual cells and create more situations where time sharing of channels becomes necessary.

Improved Level of Service

With improved network-monitoring and network-planning capabilities, the network planners have been able to react quickly to potential network deficiencies by implementing the necessary medium-term (for example, adding new channels) or long-term (for example, adding new cells) solutions. The application of dynamic channel reassignment has significantly improved the worst-case performance of cells it is applied on. In particular, AUTOCELL has successfully alleviated traffic congestion in situations where there is an extended surge in traffic demands or an occurrence of multiple faulty channels in a cell. As a result, the number of occurrences of high congestion (that is, where GOS exceeds 5 percent) has been reduced to no more than two cells a month since March 1994.

Improved Operational Efficiency

The amount of time spent by operations and maintenance staff members to collect data and generate reports has been reduced from one person-day a month to approximately one hour. Moreover, the generated reports contain data collected on each day of the month instead of on just a few selected days and contain more types of data than were collected before.

The amount of time needed by the operations and maintenance staff to check the status of certain network elements (for example, voice channels) was reduced from two hours to five minutes. With the tedious and time-consuming task of data acquisition, management, and processing automated by AUTOCELL, the operations and management staff members can devote their time and effort to more important operational tasks (such as diagnosis).

With the easy access to a rich set of data and information, the planners have been able to perform network planning efficiently. Recently, the network planners conducted a study on how to further improve the channel use of the AMPS spectrum. According to one planner, AUTOCELL enabled him to complete his task, which previously took no less than three days, in about four hours.

Framework for Continual Improvement

It is conceivable that a network engineer might formulate new hypotheses relating certain traffic or network data items while he or she browses through the various user interface panels and reports. The engineer can then proceed to verify the hypothesis against past records of traffic and network data. Once this hypothesis is certified, it can be codified into a future release of AUTOCELL, making it a bit more intelligent than before. In fact, it is this feedback loop between AUTOCELL and the engineers that holds the most promise. We envision a scenario where AUTOCELL and the engineers form a partnership where they continually learn from each other, with the continual improvement of network performance (better service, higher capacity, lower costs) as the outcome of this partnership.

Concluding Remarks

The application of AI principles and techniques at both high-level (that is, agents, agenda-based control) and low-level (that is, heuristic search) aspects of AUTOCELL has helped create a system that, to the users, exhibits intelligence. In particular, the users have been impressed with AUTOCELL's ability to smoothly gather information from the MSC, react actively to network congestion, provide value-added information and recommendations, and operate autonomously round the clock without requiring human supervision.

More importantly, the use of AUTOCELL has brought both tangible and intangible benefits to ST. Team members believe that the success of the application has been the result of the synergy of abundant data (from the MSC), computer technology (graphic user interface, database, networking, intelligent techniques, and algorithms), and the collective expertise of various operations and management and network planning experts.

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References

Calhoun, G. 1988. *Digital Cellular Radio*. Norwood, Mass.: Artech House.

Lee, W. C. Y. 1990. *Mobile Cellular Telecommunications Systems*. New York: McGraw-Hill.

Low, C. M. 1994. Frequency Management in a Cellular Mobile Network Management System. In Proceedings of the Fourth Annual Workshop on Operations Management. Singapore, The Republic of Taiwan: Information Technology Institute and the Department of Decision Sciences of the National University of Singapore.

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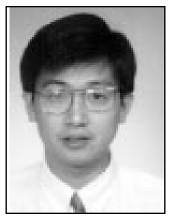

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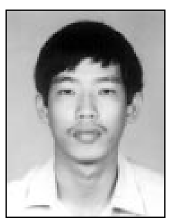

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