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Situation-Aware Wireless Networks

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ABSTRACT

The task of implementing a dynamic planning tool for wireless networks is a complex and multilayered problem. The following article explains the concept of dynamic planning and highlights the challenges involved. A system architecture that allows networks to be self-organizing is presented, and the concept of situation awareness is introduced. The resulting functionality endows network elements with the intelligence to react dynamically to perturbations. Location-aided planning is currently receiving much attention from the research community; its application to situation awareness is discussed. The use of game theory to solve resource contention in competitive scenarios is highly effective. Adaptors that are specific program modules are used to launch countermeasures and are demonstrated in this article through an example. A number of key results associated with the concept of reconfigurability are presented. Finally, a new planning paradigm based on local interaction is introduced and relevant conclusions are drawn.

DYNAMIC PLANNING TECHNIQUES

As the telecommunication industry matures it is increasingly becoming possible to provide a pervasive service tailored to the needs of individual users. Mobile phone customers can expect to seamlessly access a plethora of services in various environments. In this communication model, multiple heterogeneous networks will coexist, complementing each other by providing ubiquitous connectivity.

In order for new standards such as Universal Mobile Telecommunications System (UMTS) to replicate the success of GSM, obtaining the correct balance of service-level satisfaction to pricing is paramount. Operators will have to ascertain that in order to provide mobile connectivity at a rate comparable to fixed Internet access, the cost per bit will have to be kept at realistic levels. Subscribers will not pay a disproportionate amount of money for services even though they are technically innovative.

The requirement of providing country-wide cov-

erage and higher data rates has a direct implication for a larger number of network nodes (access points, base stations). One clever way of meeting these needs is implementation of architectures such as infostations: a sparse infrastructure is deployed close to network nodes where download at very high data rates is possible. Outside the range of the infostations only moderate data rates are possible depending on the amount of money the subscriber is willing to pay. Alternatively, smart networks that optimize resource allocation by providing capacity where it is required could be deployed.

Even though the cost of infrastructure is expected to fall according to Moore's law, operators should incorporate cost saving mechanisms within their networks to generate faster return on investment. Currently 80 percent of the capital expenditure of an operator is spent on the UMTS terrestrial radio access network (UTRAN). In order to be cost effective it is imperative to optimize the UTRAN topology. In wideband code-division multiple access (WCDMA) systems, which are inherently dynamic because of the interdependence of coverage and capacity, fixed planning associated with second-generation systems is clearly inadequate. Once the network is commissioned, the network nodes cannot be left operating on their own. An effort equal to that required in the predeployment stage is needed to maintain and support the post-deployment period.

The quality of service (QoS) delivered to users in a network can change significantly over time as a result of variability in both the traffic and the propagation environment (e.g., the construction of new buildings, the demolition of old buildings, changes in vegetation). In the case of microcells, these fluctuations can result in major changes in cellular coverage and capacity. Adaptive or dynamic networks are being proposed in order to drive down the cellular infrastructure cost while maintaining QoS in a time-varying network. More specifically, self-organizing or automated techniques have been proposed to achieve dynamic network behavior [1].

A well designed dynamic planning system should make good use of traffic, propagation, and collateral information to maximize spectral efficiency and optimize key parameters such as coverage and

capacity. This leads to efficient use of network resources and provides increased revenue for the network operator. From a user perspective, a well-planned network delivers high QoS to all geographic locations for a wide range of mobile applications.

Essentially, dynamic network configurations reduce network sensitivity to planning parameters. Through intelligence incorporated at base stations, the effects of suboptimal base station location, temporal variations, and changes in topography (seasonal variations) can be minimized [1]. This is achieved through efficient radio resource allocation and careful interference management. Using the concepts of self-healing, an initial network plan can be sustained for a longer period of time.

The system architecture for a dynamic planning tool as presented in this article aims to delineate from conventional techniques, and to look at planning as a self-organizing process. Ultimately added flexibility is brought at reduced cost. In this paradigm, the placement of wireless equipment can be performed at opportunistic locations without the need for an extensive site survey. Moreover, the return of system parameters is now automated. Statistical inference techniques, combinatorial optimization, and game theory are the main building blocks used in the construction of smart networks.

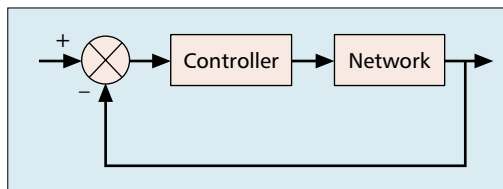
PLANNING CHALLENGES

The most important objective in post-deployment planning is to guarantee cost-effective use of existing infrastructure. Radio resource allocation in a multiservice network is complex; resource availability does not always coincide with service demand. Resource provisioning is largely dictated by the interference profile. Heterogeneous networks, customer service differentiation, and varying QoS requirements for multimedia services are additional aspects that must be addressed by allocation of resources.

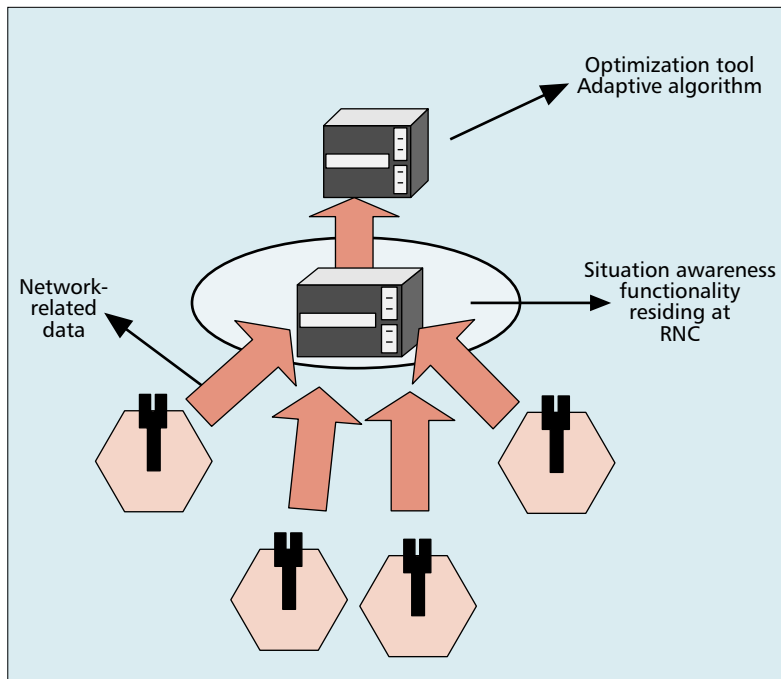
The concept of automatic planning is relatively new; most work reported to date considers a partial implementation of a complete system. An example of this includes load management systems for WCDMA. The generic architecture of such systems would be similar to Fig. 1. However, this system, while being automatic, cannot be called intelligent as it is designed for a single purpose. It operates by analyzing a large quantity of network data and controlling a single variable. For example, a forced handover technique could be applied to move users from a heavily loaded cell to one with spare capacity. A closed loop model on its own is unrealistic when a large network of several kilometers is considered with a large set of network parameters. Besides, the signaling load required to gather information from the whole wireless network would significantly reduce the available capacity on offer.

A SELF-ORGANIZED NETWORK USING SITUATION AWARENESS

A self-organizing network is a system that responds to its environment autonomously, detecting external conditions and reacting



■ **Figure 1.** Closed loop control for post-deployment optimization.



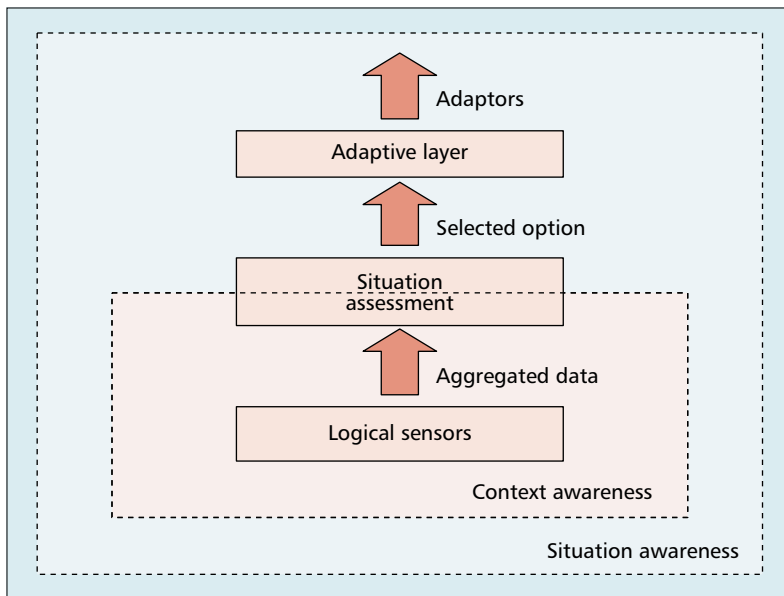
■ **Figure 2.** Cluster control planning.

appropriately [2]. We have considered two approaches to implementing a self-organized network: one consisting of the conventional top to bottom planning approach, which we call cluster control, and the second involving reversing the planning approach through the use of local interaction.

In cluster control (Fig. 2), a hierarchy among the network elements is assumed. Sitting at the top is the radio network controller (RNC), the central node overseeing the lower tier of network nodes. This central node makes all decisions relevant to the cluster with an overall objective of maximizing performance.

A self-organized system based on local interactions has a flat structure and functions exclusively in a decentralized mode. Each node makes a decision independently. The collective behavior of all local network elements dictates the global behavior of the network.

Both methods have a layered architecture, as illustrated in Fig. 3. However, they differ in the methods of interaction. In cluster control, a problem can be addressed locally or collectively. However, the controlling node is responsible for assigning and communicating tasks. In the local interaction method each network node behaves independently. They communicate with neighbors through simple rules of interaction out of which emerge global patterns.



■ **Figure 3.** The layered architecture of situation awareness.

DERIVING INTELLIGENCE THROUGH SITUATION AWARENESS

Context awareness is a popular term used to describe the process by which a mobile phone situates itself within its local environment. Situation awareness is a broader term encompassing network elements such as base stations and radio network controllers (RNCs). In addition, situation awareness allows network entities to identify their situation and provides them with the ability to make intelligent decisions.

Situation awareness is a physical layer functionality. It provides the base station with local knowledge of the current state of the network based on observations of its surroundings and is acquired through the use of logical sensors. A model commonly used in the field of avionics has been incorporated in the context of wireless networks [3]. The model has three levels; level 1 involves the perception of the elements in the environment. The base station is required to detect the relevant geographical attributes and dynamics in its vicinity. This could involve the detection of peers, establishing mean path loss or extra capacity available. Level 2 involves comprehension of the current state. Level 1 data is then used to form a holistic picture of the environment. At this stage the base station must determine the nature of the perturbation in its environment. Finally, level 3 involves the projection of future status and is essentially an evaluation function. At this stage the base station is required to initiate corrective action based on its assessment of the situation. The best option is selected on the basis of the minimal negative impact it has on the whole system.

LOGICAL SENSORS

In the case of cellular systems, information on network performance can be obtained from performance counters and measurement programs at the mobile switching center (MSC) and radio network controller (RNC). Mobile terminals can

equally be used to complement the source of primary data, as described below. They can report channel conditions in real time and act collectively as a distributed channel sounder. The information used by a network node can be broadly categorized into three groups:

Geographical information

- Location of current node position and neighbors
- Propagation characteristics of the neighborhood (mean path loss between neighbors)

Spatial/temporal information

- Performance bounds
- Available capacity
- Coverage footprint
- Seasonal variations

System information

- Services offered
- Impact of perturbations

Prior knowledge of all this information allows the network node to assess the *situation* (Fig. 4) and decide the best course of action. As such it is possible for it to decide what constitutes a deviation in performance or if internal parameters require readjustment in the light of a perturbation such as a seasonal variation.

LOCATION REPORTS

Recently, interest has grown in the use of mobile location technologies and support for location-based services. This has been driven by the high bandwidth availability in UMTS and obligations laid down by regulators such as the FCC and the European Commission. These require reporting of location from all mobile-handset-originated emergency calls to an accuracy of 50 m.

The improvements made in handset technology now offer operators the potential to develop a huge distributed network monitoring system. The ability exists to collect and report back location-based channel estimates for network optimization purposes. This leads to the possibility of adapting coverage as a function of change in the network environment or load profile. In this process the situation awareness of the network is enhanced.

Location-aided planning allows a situation-aware base station to optimize radio resource allocation and augment the radio resource management (RRM) capability of the network [4]. The accuracy of propagation models varies greatly. Generally, the very best propagation models achieve a standard deviation in the range of 8–15 dB. Significant errors and variations can arise just months after network rollout due to geographic variations. Propagation errors can rise significantly to a point where the original fixed plan is no longer appropriate.

For dynamic mapping it is important that the standard deviation be at most comparable to that of fixed prediction methods. Path loss can be derived from received signal strength indicator (RSSI) measurements; however, this is not independent of the mobile terminal. Received field strength (Vm^{-1}) is a more reliable parameter. In order to normalize the path loss measurements derived from various mobile terminals (PDAs, mobile phones, etc.) it is important to consider the type of antennas involved. As such, in the context of situation awareness and dynam-

ic planning, it is suggested that handset antenna parameters (e.g., effective area and gain) be transmitted to the base station on a control channel. Alternatively, a unique database of antenna characteristics for each mobile could be stored by the operator.

Our research shows that for adaptive coverage maps to outperform commercial fixed planning tools, a mobile terminal location accuracy of at most 100 m is required. Ideally, for best performance this should be reduced to 10 m.

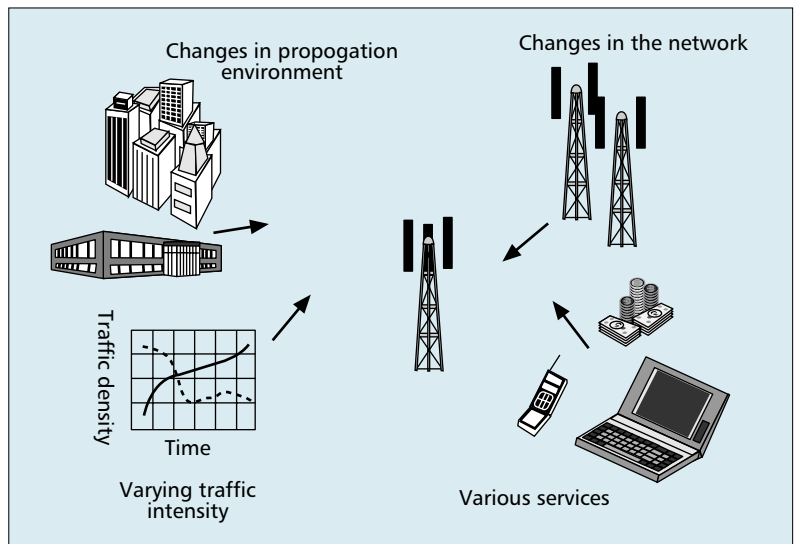
SITUATION ASSESSMENT

The situation assessment stage allows the situation-aware entity to identify its current situation and decide on the best course of action. Sensor readings from various sources are fused and encoded as a data structure following the logical sensor stage. Situation assessment then requires the comparison of data structures (patterns) with situation templates. Situation templates are logical and/or spatial relationships between constituent elements that characterize a *situation* and are similar to signal fingerprints used in location techniques [5].

Similar to real-time systems, information collected has to be preprocessed, which involves the sampling and quantizing of data for storage and manipulation [6]. The representation of data has to be carefully selected as the processing of bad information may lead to the wrong inference on the prevailing *situation*. Data is generally measured over a time interval or accumulated as a result of an event trigger. The information collected has to be temporally consistent, which involves the correct representation of the situation at the time of sensing.

For optimization or perception purposes, the data can be collected and averaged before updates are implemented. However, for situation assessment, up to five dimensions of information could be aggregated for a decision making process. The multidimensional data describes measured attributes associated with spatial regions in the network. Figure 5 summarizes the aggregation and conditioning of data in the network.

The information collected from the sensors in the network is typically noisy, and the data collected can be ambiguous. Statistical inference is a method that allows us to draw conclusions from the limited information collected. The Bayesian approach is one such technique that



■ Figure 4. Situation awareness functionality.

provides a general framework for rational inference and decision making under uncertainty [7].

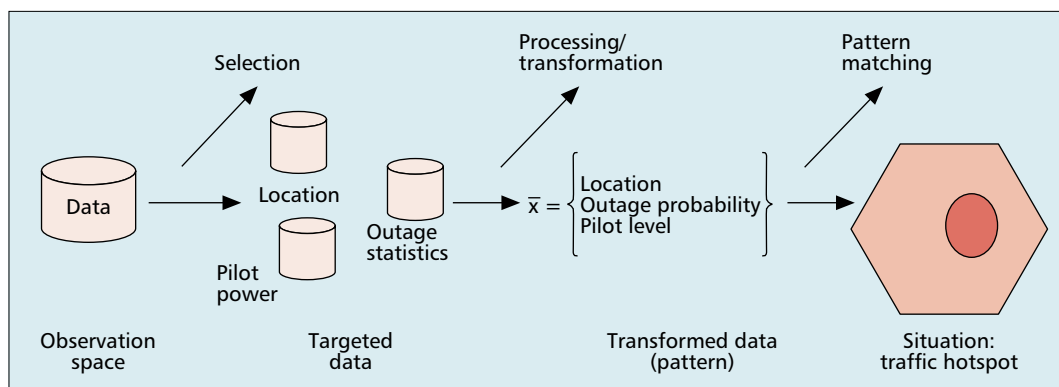
EVALUATION FUNCTION

Successful assessment requires the projection of future action in order to achieve full situation assessment functionality. This involves the ability to weigh the consequences of each available option and select the countermeasure that has the minimum negative impact in the immediate future. Following the detection stage, the network element (base station) may have to choose between two available options:

- Increase its own transmit power to reorganize the coverage boundary
- Request a neighboring base station to increase its transmit power to reorganize the coverage boundary

Each action can be seen to have an associated cost, and the base station is required to opt for the strategy that minimizes loss.

Resource sharing is not an issue in a centralized system, where a central node, or the RNC in the case of a cellular system, equalizes resources (codes, power) in order to maximize the performance of the network as a whole. In a decentralized situation, peers have to negotiate resource sharing, and a mechanism to support efficient exchanges is required. In this context,



■ Figure 5. Situation inference based on data collected from the network.

Game theory is a branch of mathematics used in the study of problems of conflicts and cooperation among independent agents. The application of these concepts to wireless systems is fairly recent and has been primarily investigated in conjunction with uplink power control in CDMA systems.

base stations do have the common goal of maximizing the performance of the cellular system.

In dynamic planning, base stations can be made to act independently or as a group. In either case the pursuit of self interest within the overall objective to maximize system performance is an important consideration. Game theory is a branch of mathematics used in the study of problems of conflicts and cooperation among independent agents. The application of these concepts to wireless systems is fairly recent and has been primarily investigated in conjunction with uplink power control in CDMA systems [8].

GAME THEORY APPLIED FOR COMPETITIVE RESOURCE SHARING

Methods developed for the centralized allocation of resource requirements of a single service such as circuit-switched telephony are not appropriate in multiservice networks like the present Internet. In present and future networks the resources are not “fixed component” entities within the network since they can be moved around and shared as required by active services. In such dynamic and highly distributed environments, prefixed and centralized resource allocation schemes cannot anticipate the needs of individual services or their willingness to pay for network resources. The resource allocation dynamics will be driven by active negotiations between network clients and agents managing the resources. A self-enforcing resource sharing arrangement that automates negotiation is most naturally implemented by using game theory [9]. The needs of services (clients) are described by their utility functions, which capture the perceived gains from an increase in available network resource. The utility function needs to be determined by each user individually. Provided that the utility functions are specified, decentralized negotiations between resource users or auctions can lead to efficient and fair distribution of network resources [10].

Negotiation between base stations is the final step in the situation awareness model, allowing the network elements to project and make an optimum decision based on all aspects of network interaction. An important concept in the field of game theory is that of the Nash equilibrium, which is defined as the set of strategies with the property that no player can benefit by changing his/her strategy assuming the other players keep their strategy unchanged. A market-based approach that optimizes the utility of a base station can be chosen for resource allocation in a competitive environment. Base stations act as independent sellers (for those having excess capacity to offer) or buyers (for those requiring additional capacity). Base stations express value using a currency that can be traded for resources. The resource price is determined by the willingness of the contending base stations to pay. For game theoretic analysis of negotiations between sellers and buyers of network resources, see [10]

Auction and Resource Sharing — An auction can be used as a mechanism to share resources without centralized control in an environment where there is no requirement for real money. A fictitious currency is assigned to the network nodes

according to the importance of their task. The progressive second price (PSP) auction rule is used in the real-time market pricing of communication. The algorithm leads to a Nash equilibrium; also, it is mathematically proven to be efficient and fair to all users. The objective in the auction is to collect bids from every competing node and allocate resources to the highest bidder. But as the payment made by the winning base station is equivalent to the second highest bid, the process ensures that the bidders pay at the correct valuation of the resource. For further details, including simulations and applications of the decentralized game theoretic approach, see [10, references therein].

ADAPTIVE LAYER

Once the situation assessment stage is completed and the corrective action identified, following a distillation process, the adaptive layer is required to implement the necessary measures. Most of the actions initiated by the adaptive layer involve optimizing the allocation of radio resources. The resource allocation problem is exacerbated by the coexistence of multiple heterogeneous networks (WLANs, 3G, etc.) providing different services and customer differentiation.

In WCDMA systems, which are tightly coupled, the network is sensitive to system parameters such as antenna transmit power, electrical beamwidth tilt, or antenna orientation. Likewise, in time-division multiple access (TDMA) systems (WLANs) the frequency allocation strategy significantly determines spectral efficiency. Given the large set of parameters requiring optimization, combinatorial algorithms such as genetic algorithms and simulated annealing are useful.

A simplification can be brought to the planning objectives by having two categories:

- Local conditions relating specifically to the access point (AP) or base station
- Global conditions describing the network as a whole

At a local level, temporal parameters such as traffic load and interference conditions are adjusted as a function of system parameters (antenna parameters, etc.). The requirement is to minimize interference by focusing on the handling of an increased traffic load without compromising call quality. There are several methods of achieving this objective in WCDMA. Load balancing is one option, whereby a pilot power control algorithm is used to adjust the size of the cellular area. Alternatively, adaptive cell sectorization can be used, in which case the sector size is adapted (system parameter optimization) to the geographical load in the cell.

The main objectives at the global level relate to capacity, coverage, and cost considerations. These issues are intertwined, and several authors acknowledge the complex scope of the optimization problem in the planning process. Economic issues are the overriding factor in planning. Although coverage and capacity should be considered together, many operators may plan their network in stages. For green field operators, the provision of coverage may be the highest priority. The main goal is to ensure that the threshold

signal strength is maintained over the service area. Capacity-based planning, especially with the variety of data services to be deployed, requires parameters other than field strength. These include user density, expected user profile, traffic models, and knowledge of different QoS classes to be supported. A possible approach to network design is to use this set of data and map it to a bit rate density.

ADAPTORS

In the projection (or evaluation) stage of situation awareness, the node or cluster weighs the consequences of all possible actions. It then selects the most economical option. Level 3 of the layered situation awareness model is then concerned with implementing the selected option.

Generally, for each problem situation there is a corresponding adaptor. An adaptor is a self-contained program that performs a particular adaptation or combinatorial optimization. If the sets of possible problems in a network and remedial actions are large, the task of designing adaptors can be challenging. One solution is to have a set of adaptors for most common problems. The only disadvantage of this method is the reduced flexibility it imposes.

APPLICATION OF SITUATION AWARENESS TO A REAL SCENARIO

Starting with a particular WCDMA microcellular deployment, a scenario is examined to demonstrate how self-organization techniques can maintain QoS over an evolving geographic environment. For this purpose, site-specific coverage prediction data is generated using a 3D building, foliage, and terrain database for a central region of Bristol, United Kingdom. An initial deployment is performed using the Combination Algorithm for Total Optimization (CAT) [4]. CAT selects sites optimized to meet initial coverage and capacity requirements. The situation awareness adaptive algorithm is then used to demonstrate how coverage can be automatically maintained despite significant changes in the propagation environment (i.e., the introduction of new high rise buildings and the demolition of existing structures).

A well developed fully three-dimensional deterministic propagation model is used to generate the time-varying propagation data required in this study. The 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 [4]. It is optimized for intracellular coverage as well as intercellular predictions (interference) between different cells in a mixed-cell network.

Once coverage prediction is complete, the CAT is used to optimize the number and location of sites required to meet operator-defined coverage and capacity requirements. CAT analyzes a list of all possible site locations and chooses the minimum subset required to meet the design criteria. As time passes, changes in the propagation environment will inevitably degrade the performance of the cellular network.

The microcellular database is modified (addition of new buildings) in order to reflect evolutions in the local environment. These evolutions can result in significant changes in the propagation between mobiles and base stations. Outage values are evaluated for both the old and new databases using identical deployment schemes.

The situation awareness algorithm detects the impact of geographic evolutions (e.g., uncovered areas or regions of high interference) and engages an adaptor to calculate new base station transmit power levels to remedy the situation. As illustrated in Fig. 6, the regions circled on the left of the picture experience poor coverage. An adjustment of the transmit power of the base stations (minimal overall interference) is performed that eventually restores the target grade of service (GoS) in the network.

DYNAMIC PLANNING BASED ON LOCAL INTERACTION

Previous sections have focused on a top-to-bottom approach where a global target is imposed; a second technique under consideration is to implement a planning model based on local interaction (bottom to top). Nature does not have a holistic approach (very complex) but rather sees trivial interaction among entities. The large-scale interaction of these entities leads to complex behavior. The same principle can be applied to a cellular network, where the local interactions are controlled to achieve a desired global behavior [2]. As an example, the high outage caused by a morphological change (e.g., erection of new buildings) in a cellular system could influence all the base stations to react collectively to oppose the adverse situation.

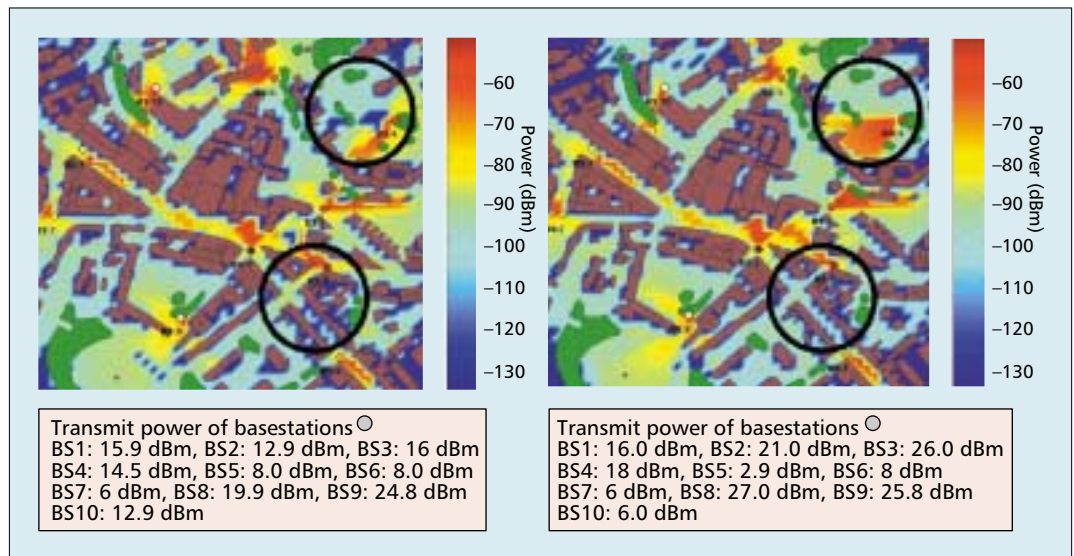
In the event that network dynamics are driven at the lowest level, simple rules are required to establish the interaction between neighboring base stations or nodes. Within a self-organized network deployed over a wide area, several processes have to happen at the same time. Cooperation or competition among network elements is the driver for local interaction. Communication is essential for local interaction and can be direct or indirect. Base stations or nodes can process information and communicate between different parts of the system.

The synergy created through the exchange of information would lead to a stability defined by the network planners. A few key microscopic interactions can be described by simple equations to form the basis of the model. The dynamics of these interactions can be fed back to influence the global pattern.

This technique would be scalable to large networks. In a future forecast it is estimated that close to 10,000 microcells would be required along the M25 highway corridor (the London ring road) to provide high capacity. Such deployment is currently not feasible because of the rollout cost and the problems involved in controlling such a dense cluster. If the cost barrier is removed, the only obstacle remaining is control of such high-density microcells. This could be achieved by a self-organizing network using local interaction.

Generally, for each problem situation there is a corresponding adaptor. An adaptor is a self-contained program that performs a particular adaptation or combinatorial optimization. If the sets of possible problems in a network and remedial actions are large, the task of designing adaptors can be challenging.

Significant work remains to be performed in the field of reconfigurable networks based on situation awareness. Our work has focused on developing system architectures for a dynamic planning system that could bring significant cost savings to the operator.



■ **Figure 6.** The picture on the left shows a degraded coverage; that on the right illustrates the improvement with situation awareness.

CONCLUSIONS

Significant work remains to be performed in the field of reconfigurable networks based on situation awareness. Our work has focused on developing system architectures for a dynamic planning system that could bring significant cost savings to the operator.

With regards to planning challenges, we have presented the main building blocks to achieve situation awareness. Two methods of planning were presented. The cluster control method provides centralized control over a medium-sized network, typically 150 base stations. The bottom-to-top approach, on the other hand, is still a conceptual planning method where network nodes are assumed to have very little intelligence. Simple interactions govern the behavior of the network nodes. In the local interaction approach the objective is to minimize uncertainty within the network in order to maintain a state of awareness. This is in opposition to the link level process, where the goal is to maximize uncertainty to maximize capacity.

The actual challenge is to design dynamic networks where it is possible to characterize local interactions and achieve the desired behavior. How network-related information is coded, accessed, and acted on is also crucial. A network governed by local interaction has the benefit of being immune to instabilities.

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BIOGRAPHIES

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