RF interconnect/interface

Designing the cellular network infrastructure

Cellular network design for greater profits and better quality of service.

By John Arpee

Initially, cellular networks were designed for maximum coverage at minimum cost.

At one time, Sacramento, CA was covered by eight cells[1] and New York City required no more than 24 cells. Now Sacramento requires hundreds of cells and New York is served by well over 2,000 cells.

The most amazing thing about all these additional cells is that there is no clear business case for them. The cells are required to support the additional traffic the networks now carry. Without them, there would be even more interference and quality degradation than exists today. The problem is that it is difficult to define the value of a new 'capacity' cell and to know where to draw the line or how to set priorities.

Network planning – the key to tomorrow's wireless infrastructure.

Network design criterion

Every design decision is based on four criteria: coverage, capacity, C/I, and cost. Coverage is how much area is served (km^2). Capacity is the ability to carry traffic (Erlangs today, bits tomorrow). C/I is a commonly used term that references the "carrier-to-interference ratio," but in this article we will define it as "the ratio of the signal you want to the signals you don't want" (dB). Cost is defined by $.

These principles apply to all cellular networks including code-division multiple access (CDMA) and 3G. In FM and time-division multiple access (TDMA) networks, interference has a direct impact on quality. Where there is low C/I there is poor quality. In CDMA networks, the network responds to high interference levels by increasing power. Because the total power output is limited, high interference can result in reduced capacity. And, if the interference is too severe at a location, the system may not be able to compensate. Another effect of cells sending too much signal out is the increases in overlap between cells, which also robs network capacity. Therefore, in CDMA, a direct relationship exists between interference and capacity.

In the mid 1980s, cellular design was all about coverage and cost. Because there was little traffic initially, capacity was not an issue. The spectrum-to-traffic ratio was large, therefore interference was easy to control.

In the early stages, sites were located on mountains, tall buildings or tall towers. New sites were periodically added to extend the footprint of the network. Whichever company could show the most covered area in its marketing literature won. The business case was straightforward. Everything was based on the projected traffic. Planners assumed that traffic on a cell was roughly proportional to the population covered by the cell. Over time, the traffic for the same population might increase with increasing penetration, but the proportions were assumed to hold. To calculate the cost of a new cell, the planners would use the traffic estimate to calculate the number of required channels. The number of channels plus the usual fixed costs determined the cost of the cell. The revenue generated by the cell was directly related to the amount of traffic.

Capacity cells were not initially required, but eventually the spectrum was used up and frequency reuse began abruptly. At this point, omni-directional antennas were replaced with directional antennas to form three- or six-sectored sites. This had ripple effects. The quality immediately degraded because of the sudden jump in network complexity and an increase in adjacent and co-channel interference. The cost-per-site increased immediately because there were now more antennas, more costly equipment to manage them and more channels required because of the loss of trunking efficiency. This sudden barrage of changes often resulted in changes in personnel and organizational structure.

In defense of quality

The fundamental problem, the industry discovered, is that there is no effective way to form a business case for capacity cells. According to cellular theory, capacity cells are required to maintain minimal C/I targets. The theory assumes perfectly flat terrain and evenly distributed traffic. Once the number of required channels in a sector reaches a threshold, the theory requires that a "split cell" be built to maintain acceptable C/I.

Some operators attempt a business case by estimating the predicted amount of traffic that will be carried by the new capacity cell. They use the traffic estimate to calculate the revenue for the cell. However, the underlying assumptions behind this method are false. If a cell is purely off-load, it will not generate any new traffic. This is because the traffic that it carries, by definition, is off-loaded from other cells. The net increase in traffic, and therefore in revenue, is zero.

Other operators justify new capacity cells with an increase in revenue. They explain that new urban cells generate new traffic while minimally off-loading neighboring cells. This interpretation assumes that usage increases because new cells improve building penetration and quality. Because the off-loaded traffic is low, and there is an incremental jump in traffic, it is argued that such a cell is actually a ‘coverage’ cell, not a ‘capacity’ cell. What is interesting is that a direct relationship exists between quality and revenue.

The rules of thumb

Typically, operators find that new capacity cells do not result in an incremental increase in traffic. When there is no direct revenue benefit, engineers resort to rules of thumb (ROT) to justify new capacity cells. Planning new cells based on rules of thumb is successful to the degree that the assumptions behind them are valid. In practice, the rules are bent when it is clear that the assumptions do not apply. Examples include micro-cells in high traffic areas where the RF is clearly limited to a confined area and directional cells along major traffic corridors.

This should make financial managers uncomfortable. There is no way to measure the value of individual projects. Typically, engineers ask for lots of capital to build many new cells and other projects to improve quality. Then management reacts with horror to the cost of the proposed projects, makes an arbitrary decision, and tells the engineers they can build fifty cells; leaving it to them to decide where to locate the cells.

The solution is to define the economic value of improving quality or preventing quality degradation. If such a definition exists, and there is a reliable way to predict the quality improvement that will result from a capital investment, then the economic viability of a project can be found by subtracting the capital cost from the value that results from the quality improvement.

There are various arguments against defining quality. Some people argue that it is unrealistic to assign value to quality because quality is subjective. Amazingly, other people claim that quality has no significant impact on revenue. When companies fail to define quality standards, they delegate quality standards to their engineers. This is unacceptable. If quality truly has no economic impact, then operators can save billions of dollars by not building new cells and allowing blocking and interference to increase. Churn, flaming news articles and customer lawsuits are merely distractions.

Current design methods rely heavily on ROT. For example, when the traffic on a sector reaches 12 Erlangs, it is time to build a capacity cell or allocate more spectrum. According to ROT, a criterion indicates when a new cell should be added, but it is up to the engineer to ensure that the new cell off-loads a decent amount of traffic without causing interference. Likewise, if one of the original cells in the network causes a huge amount of interference, it is up to the engineers to persuade management that it is worth building three smaller replacement cells so that interference may be controlled.

There is a tacit understanding of the trade-offs between coverage, capacity and quality, but no business case exists to support good design. A good engineer constantly balances the capacity and interference properties of new cells that they plan into a network. Design decisions regarding quality are made intuitively and the success of the outcome depends on how well the engineers negotiate with management. This is a sloppy way to run a business and it disintegrates when decisions need to be made with regard to multiple overlaid technologies and classes of service.

The value of quality

We can debate the value of quality for a long time without reaching any conclusion, but the networks that are in service today are nominally designed to meet certain quality targets. Therefore, an implied value of quality can be calculated. To derive the implied value, a simple model will be developed that defines total network cost as the sum of capital plus an unknown quality cost. The challenge is to have a model that adequately describes the trade-off between cost and quality without being too complicated.

To simplify the calculation, work with a degradation score:

$q = 1 - i$,
q = quality $(0 \le q \le 1)$
i = degradation score $(0 \le i \le 1)$

The most critical, and the most controversial, element in deriving the value of quality is a simple model that relates network load to quality. Our assessment is that a square law relationship is accurate for TDMA networks with more than 20 cells. It has been repeatedly demonstrated that this relationship exists by performing a series of optimization runs at increasing traffic loads. As traffic is increased by the same proportion across the network, the required number of channels per sector increases. Each increase in the channel count requires a new optimization run and the amount of interference increases with the square of the traffic load. This makes intuitive sense because a square law relationship is simply the second term of a Taylor series.

For CDMA and universal mobile telecommunications system (UMTS) networks, it may be more appropriate to use a function with a higher power of t. Those networks make extensive use of features that adapt to the RF environment. Quality is maintained until the network cannot sufficiently compensate and then quality degrades rapidly. Depending on how the network quality is modeled, the rate of degradation can be more or less abrupt. Skepticism exists about quality models that assume that overall network quality suddenly degrades at some magical traffic level. In an ideal network with every cell equally loaded and similar radio propagation characteristics, there may be some kind of abrupt degradation as all cells approach their capacity limits at the same time. In reality, however, conditions vary and quality degradation begins in traffic or interference hot spots. As the traffic grows, the affected areas spread out from the initial hot spots.

To be reasonably flexible without making the model too complicated, use the model below to relate degradation to traffic load:

$$i = \beta\left(\frac{t}{\rho}\right)^{\gamma}$$

i is the degradation score, t is the average traffic per cell, and β, γ, and ρ are arbitrary constants. This model reflects a general relationship for a market.

A more sophisticated model is typically required to determine the appropriate values for the constants. For example, there might be a sophisticated model of a CDMA network that considers the radio propagation, traffic density, error correction and the behavior of the coder/decoder (CODEC) to produce a degradation score for a particular traffic level on the network. Running the models multiple times at various traffic levels, an engineer could tabulate a function that relates degradation to traffic. This simple mathematical relationship is used to make a point, but it is also possible to use the tabulated values directly.

Inserting the degradation model into an equation for total network cost (TNC), use:

total network cost = capital cost + interference cost =

$$= \frac{CT}{t} + \alpha i T$$

$$= \frac{CT}{t} + \alpha\beta\left(\frac{t}{p}\right)^{\gamma} T$$

C = cost-per-cell
T = total network traffic

By definition, T/t is the number of cells in the network. The capital (CT/t) is the number of cells times the capital per cell. Ignore the capital invested in switches, service centers and other overhead costs to ignore any cost that is not a function of *t*. In other words, additional costs may grow with the total traffic (T), but if they do not depend on the traffic per cell, they do not provide any information about how the air interface should be optimized. Ignore the savings provided by improved trunking efficiency because the only interest is in broad relationships. The equation is represented graphically by Figure 1.

Smaller Gamma values result in more shallow curves, and larger exponents result in sharper curves. ROT design criteria essentially assume Gamma = ∞. When Gamma = ∞ the total cost is equal to the capital cost until a threshold is reached and then the cost explodes. When Gamma = 2, we see that the average traffic per cell can vary by about 10% without a significant change in total cost. The total cost is roughly constant because the cost due to increased churn and decreased usage offsets the improved capital savings. As the traffic increases beyond 20%, the churn and usage costs accelerate dramatically and outweigh the capital savings.

Taking the first derivative with respect to *t*, the optimum traffic per cell can be found:

$$t = \left(\frac{C\rho^{\gamma}}{\gamma\beta\alpha}\right)^{\frac{1}{\gamma+1}}$$

To find the implied value of quality, assume that the initial traffic-per-cell is set for optimum financial performance and rearranging:

$$\alpha = \frac{C_0 P_0^{\gamma}}{\gamma\beta_0 t_0^{\gamma+1}}$$

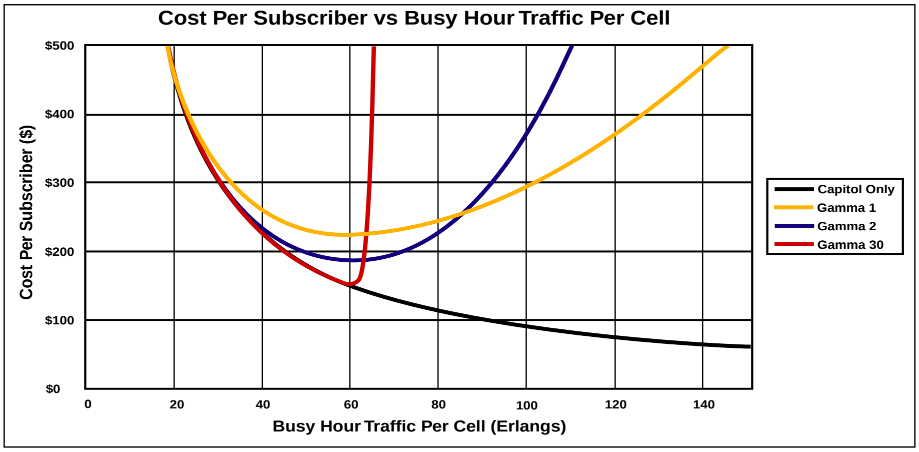

Figure 1. Cost-per-subscriber vs. busy hour traffic-per-cell.

This constant allows the determination of the dollar cost associated with a degradation metric. The units must be defined jointly with the units of the degradation metric so the product of the two results in dollars-per-Erlang. It is important to note that the value of quality has been reverse-engineered . In reality, the value of quality depends on pricing plans and the competitive environment.

Inserting the formula for alpha back into the equation for *t* for:

$$t = t_0 \left[\left(\frac{\rho}{\rho_0} \right)^{\gamma} \left(\frac{C}{C_0} \right) \left(\frac{\beta_0}{\beta} \right) \right]^{\frac{1}{\gamma+1}}$$

Set $\gamma = \infty$ to model ROT-based design criteria. Assume that traffic has no impact on quality below some threshold and then quality collapses abruptly as the threshold is reached. In that case, the optimum traffic is insensitive to the capital costs:

$$t = t_0 \frac{\rho}{\rho_0}$$

If $\gamma = 2$, the optimal traffic level depends on the capital cost and the rate at which quality degrades with traffic. The formula indicates that 25% more cells should be built if the total cost for a cell is cut in half. The β value is the gateway for evaluating the economic benefit of any proposed capital investment from new cells to new quality-enhancing technologies.

Practical application

Once it is accepted that quality has measurable value, albeit approximately, an ROI can be generated for any proposed project including capacity cells or the introduction of new interference-reducing technologies. To do this practically, there must be tools that predict the quality impact of proposed changes with a tolerable degree of accuracy. The ability to predict quality impact is essential to produce an ROI prior to implementation.

After a change is implemented, the impact on quality should be measurable, but this is not a trivial exercise. First, the impact on performance metrics is obscured by the amount of inherent noise in the metrics. Second, from a value standpoint, a single metric should be dealt with that indicates overall network quality. Instead, there are usually several incomplete or overlapping (ie. correlated) statistics. The solution for the first problem is to average the data over a sufficiently long interval. There is a tendency in the industry to only include statistics from the 10 busiest hours of the month and discard the remaining data. This is a statistically nonsensical practice. By including more hours of data, the accuracy can be improved dramatically.

Typical network performance metrics include: dropped calls, blocked calls, bit error rate (BER) and frame error rate (FER). E_b/N_0 or C/(I+N) signal quality data can also be collected. The network performance metrics are results of the signal quality. The goal of the engineer or optimization software is to maximize the signal quality, which should improve the resulting performance metrics.

One way to obtain a single quality metric is to only consider BER data. The logic is that performance statistics are correlated to BER. FER is directly related to BER. For a given network, histograms of the BER can be produced, as can predicted signal quality and measured signal quality. To apply TNC design criteria, map these histograms to scalar values. Using this approach, design tools can be obtained that produce predicted quality metric, which can be used to evaluate the merits of a project. Data can also be collected to evaluate and improve the accuracy of the design tool. This approach is examined in the case studies below.

ROI case studies – new cells

One of the main limitations of ROT is the inability to produce an ROI analysis for a new capacity cell. By placing a value on quality, an ROI analysis can now be performed. When a new capacity cell is added to a network, it reduces the traffic-per-cell by definition. If it causes about as much interference as it prevents, then the b of the network will remain the same. Savings will result because of the reduction in interference, which results from the reduced traffic load per cell. The ROI is simply the reduction in the TNC. The increase in the CT/t is the capital required for the new cell. The predicted decrease in the aiT term must be greater than the capital cost to justify the investment.

A capacity cell can be even more worthwhile if it reduces the amount of interference in the network. If the new cell is close to a traffic hot spot and has antennas that are low enough not to interfere with other cells, then interference will be reduced. In the quality cost model, the reduction in interference is indicated as a reduction of b. If many new cells have improved interference properties, there can be an overall improvement in quality or more traffic can be carried per cell without sacrificing quality.

Interference mitigation

Visiting the 3GSM show in Europe or the Cellular Telecommunications and Internet Association (CTIA) show in the United States, one is amazed by the number of companies offering some technology to “reduce interference and increase capacity.” It is impossible to evaluate these claims using ROT, but it is possible using TNC. Consider a menu of typical options that an operator might pay to use:

1. *Hire more engineers*
2. *Network features*
    - *Frequency hopping*
    - *Automatic channel allocation*
    - *Automatic power control*
3. *Antennas*
    - *Custom antennas*
    - *Smart antennas*
4. *Better tools*
    - *Automated frequency optimization*
    - *Measured path loss data*

Admittedly, it is difficult to come up with a model that relates β to the number of engineers, but the compensation package might be changed. Most engineers have a bonus that is related to the performance metrics. It might make more sense to reward engineers based on the total network cost, which includes capital efficiency.

The other options can be evaluated by setting up trials that demonstrate the impact on performance metrics. The quality impact is then converted to dollars. In some instances, it is difficult to assess how much the amount of quality improvement is due to a new option and how much is simply due to increased attention to the network. The way to prevent this confusion is to give the market engineers a chance to clean up their market before testing any new methods. The resulting quality improvement can then be converted to dollars.

Once a new technology has been accepted, the engineers must have tools that guide them in the application of the technology. For example, smart antennas have been shown to improve performance, but the amount of traffic or the amount of improvement in a particular sector may not be sufficient to justify the cost. Many attempts to model the quality improvement simply add a few dB to the predicted C/I. This approach is woefully inadequate for most applications. The predicted degradation must consider the probability and severity of interference to produce a reasonable, accurate estimate that can be correlated with BER.

Multi-mode networks

ROT is marginal, at best, for single-mode networks. For multi-mode networks, it is hopeless. As 3G becomes a reality, operators will be faced with supporting legacy 2G mobiles and multiple classes of 3G voice and data services. They will have to consider spectrum allocation, target quality levels, an array of interference mitigation techniques and changing market conditions.

TNC can be easily adapted for multi-mode networks by including a separate quality cost model for each service and a means for analyzing the intra and inter service interference. The total degradation cost is the sum of the degradation costs for each service. If the cost model and the models for predicting quality are reasonably accurate and well-defined, optimization functions can be developed to jointly optimize the spectrum allocations and the financial performance of each service.

The final countdown

The arrival of complex multi-mode networks and the need for greater capital efficiency will force the network operators to adopt objective design methods. ROTs have been responsible for present-day conditions, but they do not scale and they are useless for making trade-offs between capacity and quality or deciding how to allocate spectrum and capital between multiple services. Placing a value on quality is admittedly approximate, but it is less approximate than blindly following rules of thumb.

RF

[1] In this context, a cell is a bank of radio transceivers connected to one or more transmit antennas and, typically, two receive antennas with practically identical patterns. There are usually one or three cells per location.

About the author

John Arpee co-founded ScoreBoard, in October 1993. He is responsible for the engineering department, which develops algorithms and methodologies for the company's new products and services, and works with customers to develop network growth strategies. Arpee has more than 15 years of radio engineering experience. Previously, at LCC International, he worked on a variety of early stage and mature markets both domestically and internationally. He grew the engineering department from 14 to 30 engineers that served most of LCC's North American customers. Prior to joining LCC, he worked at MCI Airsignal. He has written numerous articles and training documents, including *A Primer On Cellular System Planning*, 1990 April, Telocatur; and *NEXRAD Interactions with Radio Astronomy Telescopes*, DoD, Electromagnetic Compatibility Analysis Center, Annapolis, MD.

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