Technology White Paper

Capacity Constrained Smart Grid Design

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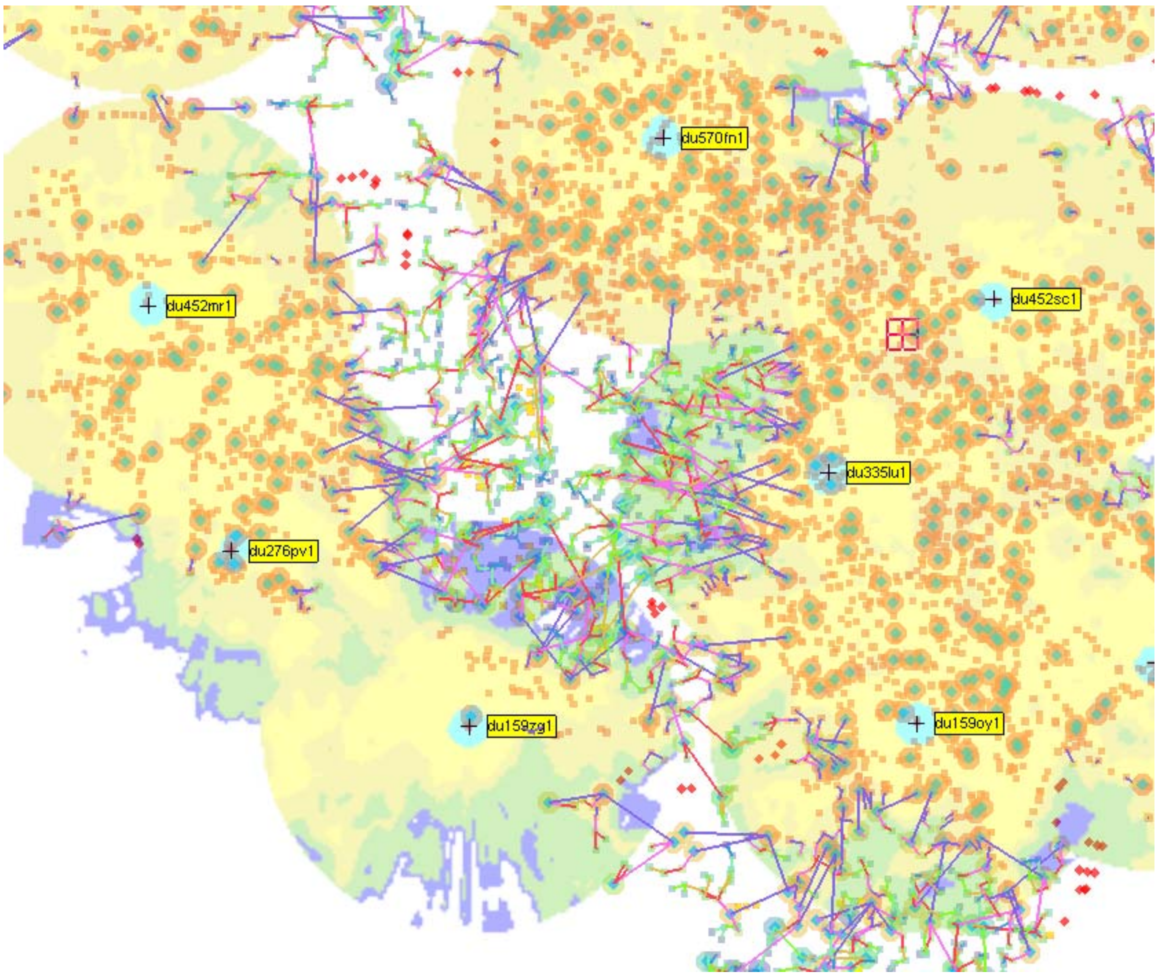

Introduction

Wireless Radio Frequency (RF) Mesh systems are frequently used for Automated Meter Infrastructure (AMI) networks where data is collected from meters via a multi-level interlinked and hierarchical wireless network. These networks need to be designed using sophisticated RF planning tools that have the ability to optimize the use of wireless infrastructure and spectrum and thereby improve network performance and reliability.

Where there is a relatively small and straightforward network (i.e. no repeaters and very limited meshing) and where the only goal is to cover the meters with a given RF signal level as provided by a selection of transmitters, one could use a simple area study. However, as networks grow in size and scale, other constraints need to be factored into the design including the effect of individual link capacity on system-wide performance.

By including these capacity constraints as an element of an overall network design at the planning stage, one can achieve a far more efficient and cost effective network design than can be achieved by simple ad hoc estimations followed by expensive field measurement/device adjustment iteration.

A well designed network will consider the intrinsic constraint on each of the many possible RF paths between elements as well as the cost of each element type. This will result in an optimally balanced system with an evenly distributed load. This in turn improves network resilience and increases the overall system data flow. In addition, areas which are underserved can be easily indentified in advance of build-out and the network design modified to accommodate them, resulting in a low cost, high performance and easily scaled wireless network design.

This paper sets out the factors affecting a capacity constrained network design for a large scale AMI system and proposes an intuitive methodology that can result in an effective and efficient network design.

It is worth noting that this method does not include a dynamic analysis of traffic and its effect on network throughput and latency. Network loading and the effects of traffic patterns will undoubtedly have an effect on performance as well, but these degradations will be in addition to the underlying structural limits imposed on the network by the factors described here. What is presented instead, is a methodology for designing a system where the average statistical load will be evenly distributed (assuming a uniformly distributed traffic pattern) with an optimal number of system resources by considering such elements as device cost, maximum link throughput, hopping tree depth and repeater chain length constraints.

Capacity Constrained Network Topology

Complex large scale AMI networks are essentially a tree structure consisting of a hierarchal series of elements starting with collectors wirelessly connected to meters or clusters of meters. In very large systems the network may also employ a network of repeaters which in turn communicate with other repeaters/collectors and finally to individual meters or clusters of meters (Figure 1 below). Each link is established via an RF path which is dependent on the type of equipment being deployed and by its RF environment (height above ground, antenna type and orientation, clutter effects and etc.)

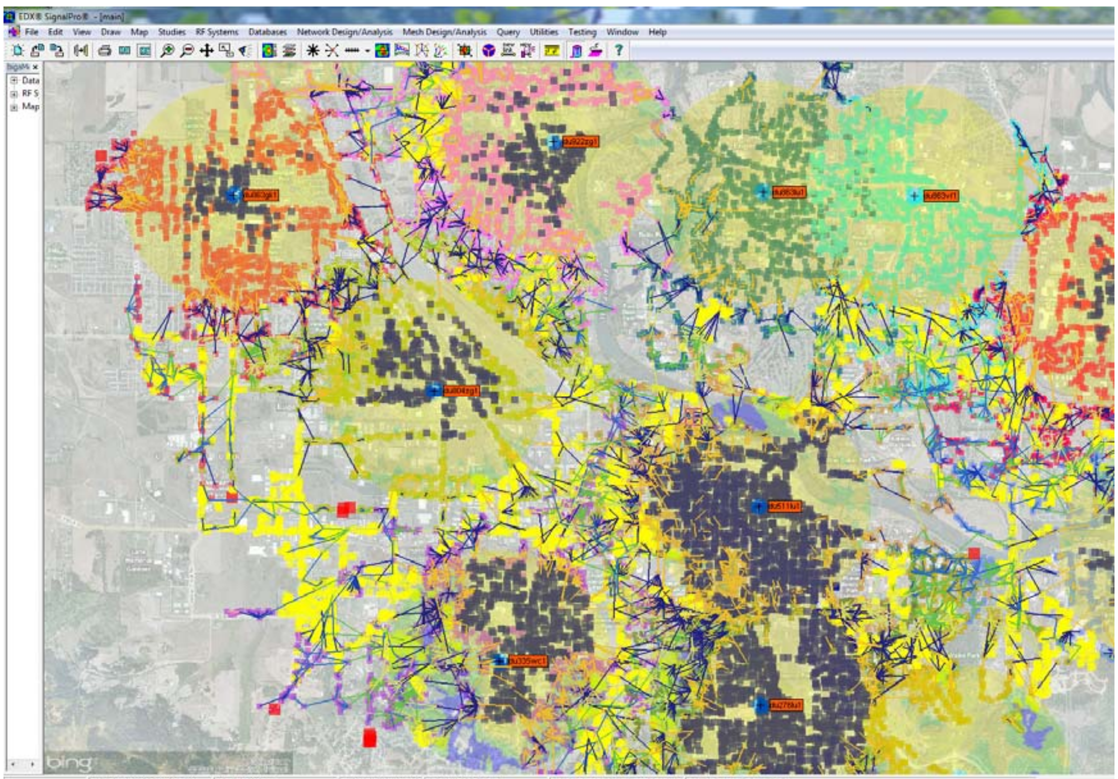

Figure 1: A typical deployed AMI Network Design

Each link in the network has its own intrinsic capacity constraint in terms of available data throughput that is supported by the particular link. The capacity in terms of maximum data throughput for each element type is defined as a link constraint.

This constraint is a function of the devices themselves as well as the RF link between the devices.

Hopping and Chain Depth

An additional constraint is the number of allowable levels (or hops) in the tree structure. Operators usually specify a maximum hopping depth for the system. "Hopping depth" does not refer to the number of packet hops being made between devices, but is related to the physical tree structure itself. Essentially, a device should only forward packets beyond itself to a certain tree depth, creating a system wide design constraint on what should be considered as reachable by the network.

Without a limit on tree depth, a packet could be forwarded many levels via many routes increasing latency. In addition, each new route created by a hop increases the statistical chance of failure. And, each failure may require a retransmission all along a particular route (a chain), requiring additional system resources at every step of the way, thus consuming additional data bandwidth and reducing overall network capacity.

Initially, AMI systems were designed for simple meter reading where data speed was not a factor. However, operators are now looking at adding support for Distribution Automation features and other emerging system operation/control features. These new features can require high data throughput with low latency. The requirement to optimally use system resources to improve available bandwidth and to meet latency targets is a critical factor in system design as well as affecting overall system cost.

Use of Repeaters

If the data link from a collector to a cluster of meters cannot be established because it does not meet the minimum RF design parameters, a low-cost repeater is often used to extend the effective range of the collector rather than add another expensive collector near the meter cluster. A repeater can be considered to be an RF forwarding device or range extender. It has its own characteristic RF requirements as well as limits on the number of chained repeater to repeater connections.

As described earlier in this paper, the network represents a complex point to multipoint star tree structure layered on top of individual mesh clusters with many millions of potential paths between the individual RF nodes. A proper RF analysis of this system is immense. In fact the task is so complex that without proper study tools the designer resorts to simply over provisioning the system with an excess of RF coverage, resulting in an unnecessarily expensive implementation. But, this approach guarantees neither good performance nor resiliency. The effects of capacity constraints described in this paper will manifest themselves even if there is an excess of available radio signal at the majority of the devices. There are two main reasons for this. One is that there is excessive RF interference from multiple transmitters generated within large overlapping coverage areas and two, because system performance is highly sensitive to the negative effects of marginal links. These marginal links create much system degradation and are a common source of potential failures.

Importance of Optimal Planning Methods

There are many reasons for operators to care about the optimal design of a system, the most obvious being cost of initial deployment. However, there are several other factors which should be considered and are goals of any optimal planning exercise.

- Ensure system-wide redundancy and resilience
- Ensure equal or at least adequately balanced performance at each node served
- Identify and remove outliers which are underserved or which critically affect performance elsewhere
- Indentify the critical network points (so called Branch Cuts, or nodes through which traffic preferentially flows) where one node becomes a critical point of failure
- Balance communications load distribution throughout the network
- Minimize latency through the system
- Preserving bandwidth for future applications
- Ensure future scalability

A useful example of where capacity constraint can directly affect system-wide operation is in a battery-powered meter network. In this type of deployment each end node and (possibly) the repeaters are battery powered. The repeater may have a larger battery and augmentation such as solar but is still limited by the maximum number of battery charge/discharge cycles. The system is provisioned based on these battery limits as an operational constraint given the obvious practical limits on battery replacement costs and time.

Each time a packet is forwarded by or through a device it consumes some processing and RF transmission power and therefore battery energy. If a packet is forwarded many times, it will consume a correspondingly larger amount of the total system battery energy. Practical constraints on the RF link and on the tree/hop depth may force traffic along one particular path rather than being broadly distributed via adjacent nodes, creating resource limited paths and critical failure points. Nodes which, through intrinsic network design, carry far more traffic than others will become critical points. These nodes will deplete their resources much faster than planned and will require new batteries far sooner than the system designers anticipated.

Designing An Optimal Network

Typical design of all RF networks involves some level of iterative process. But in AMI network with potentially many millions of RF links, design automation software is critical. EDX SignalPro® combines GIS mapping capabilities with statistical propagation analysis and automated network layout tools that provide for efficient dimensioning and placement of infrastructure equipment in even the largest AMI networks. Such design software incorporates a three-dimensional model of the geographical area of interest which is built up using a digital terrain elevation model, land use (clutter) data and building/structure data. An accurate 3D model of the radio environment is necessary to ensure that the physical issues that affect the RF performance of a complex AMI network are accounted for in the design. Once this 3D model is created, the planning of the complex mesh architecture can be accomplished in an intelligent way that respects the unique physical issues of the service area as well as the capacity constraints of the vendor’s equipment.

There are a number of vendors that supply a variety of AMI mesh equipment. Most of these vendors offer the three basic network components which are, the meter, the repeater and the collector. A typical network architecture is show in Figure 2.

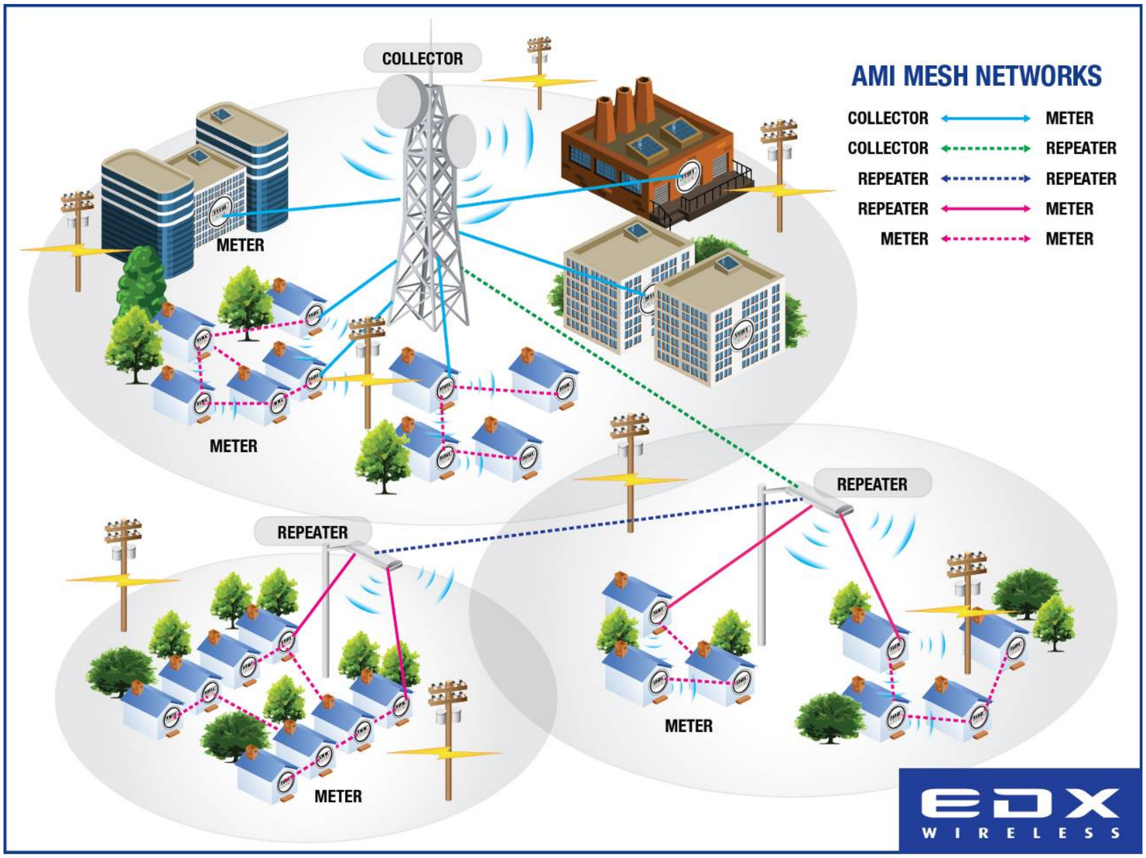

Figure 2: AMI Mesh Architecture

Collectors link directly to meters and to repeaters. Repeaters link with meters and to other repeaters, and meters can 'talk' to every network element, including directly to other nearby meters, forming a hybrid mesh and tree structure. With this large number of potential links, the network design tool must allow for millions of link calculations to be performed in a short amount of time. EDX SignalPro has been designed to efficiently scale for these calculation requirements. In addition, the planning tool allows the network planner to impose individual vendor specified capacity constraints on the various network elements such as meters, repeaters and collectors

An Iterative Design Methodology

The design process for optimizing a capacity constrained network can be outlined by the generalized iterative process shown below:

Design Process

Define service boundary. Define link budget and constraints for each network element type.

↓

Using a pre-defined scaling metric, specify the number of collectors desired.

↓

Run an Automated Collector Placement study to create initial collector locations.

↓

Confirm and adjust these locations to specify existing or desired locations.

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Generate an area study to produce an initial reference coverage design.

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Use the Capacity Constrained Mesh study and integrated Automatic Repeater Selection study to determine the optimal placement of additional repeaters.

↓

Identify critical nodes and zones that are over-capacity, beyond hopping limits and RF isolated

↓

Modify the design to add resources to critical nodes and underserved areas.

AMI RF Mesh Design Methodologies

Traditional Coverage Approach

A traditional "cellular telephone network" approach to designing AMI mesh networks is based on a simple coverage analysis of the various network hierarchy layers, such as Collector to Meter, Repeater-to-Meter, Meter-to-Meter and etc.

Typically, this design methodology begins with an initial collector site layout based on known assets such as electric substations. Collector sites are located based on an average collector coverage radius value. This radius value is determined by defining the largest distance a meter can be away from the collector and still be able to mesh back through the meter-repeater-collector layers. This distance value is variable based on performance requirements as well as geographical constraints.

Once the collectors are placed, a collector-to-meter coverage study is performed to find the initial coverage area of the collector. Based on this analysis, repeaters are then added manually to fill in coverage for those meters that are out of range. Again, these repeaters are placed based on a generalized statistical repeater radius value without any attention paid to whether the repeaters have an actual physical link or viable (non-constrained) mesh route to a collector.

This manual methodology often leads to over-provisioning of repeaters. Unfortunately, when network problems arise after deployment the typical way to attempt to solve it is by filling in with even more repeaters even though the problems may be in fact caused by over-provisioning. This ends up further increasing the cost of system but reduces overall performance due to an increase in mesh hopping and associated rise of the noise floor. Moreover, this simple empirical coverage-only approach does not consider capacity aspects which can further contribute to decreased practical network performance, and it does not identify meter nodes that may have a physical connection into a collector but are unable to connect due to collector overload.

In summary, a 'coverage-only' approach does not analyze individual mesh links, is highly iterative and is time-consuming both in the design and deployment phases. It often results in a network design that is improperly configured, leading to a lengthy and iterative (and thus expensive) deployment phase while delivering an underperforming network which is also difficult to scale further.

Area Coverage Design Example

Figure 3 below illustrates a coverage based approach designed using the empirical radius-based layout method.

This design used about 300 repeaters based on the assumed collector coverage radius. Doing this resulted in an overbuilt network. The large number of repeaters reduced the overall performance of the network by increasing the noise floor and the hop count. The design also resulted in long repeater chains which added latency and by concentrating the paths back to the collector reduced resiliency in the event of a failure of one of these critical chains.

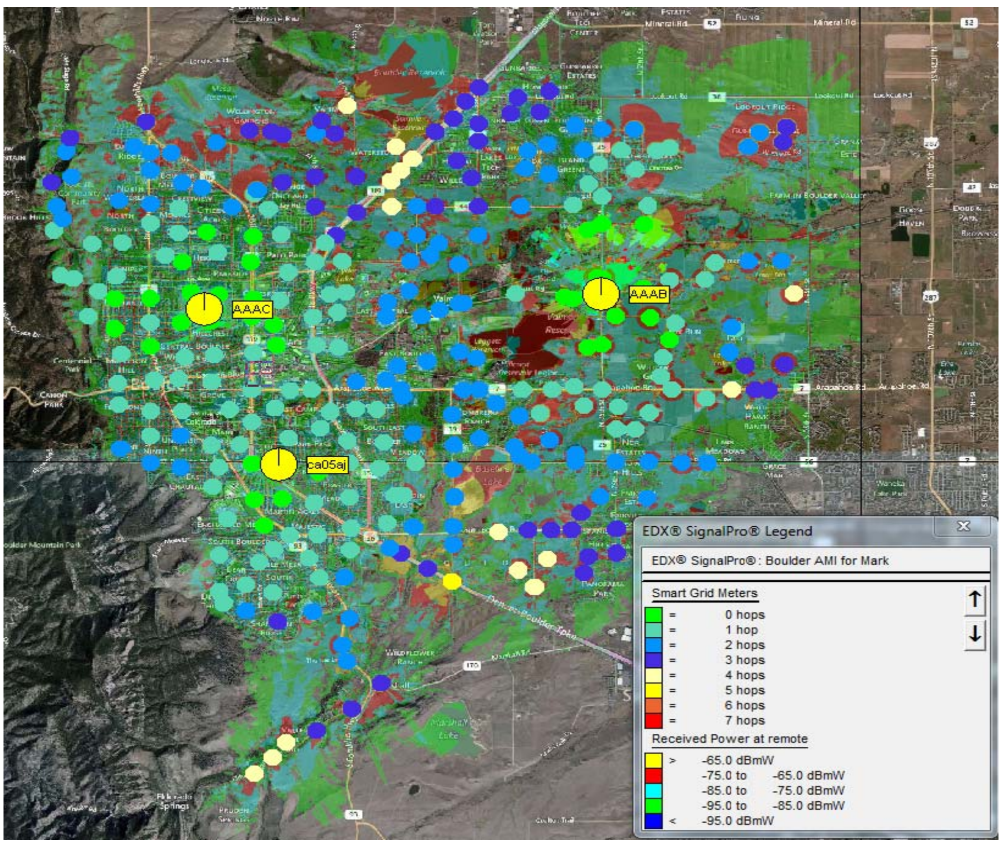

Figure 3: Simple coverage-only Based AMI Design

It is again worth noting that this is not a dynamic analysis and meshing may help to compensate for the flaws in this simple design method by rerouting around failures.

However this design will likely result in the use of suboptimal paths that will be less reliable while reducing capacity and possibly exceeding hopping constraints with an attendant increase in system latency.

Capacity Constrained Mesh Approach

A more effective approach begins with modeling the physical layer by applying individually unique device characteristics and also applying actual vendor specific capacity constraints. The success of an AMI deployment is built on an accurately designed physical layer that respects the capacity and hopping limitations of the network equipment. Designing a robust physical layer is extremely important and therefore one must use a design methodology that matches the network architecture being implemented. This begins with a methodical process to calculate potential link permutations for each of the various device combinations. Each link calculation that EDX SignalPro performs considers terrain, morphology (land use) and buildings creating a detailed RF physical layer model. This removes the guess work of determining if a meter will connect to another meter or device.

This is a major difference between using empirical coverage-only analysis methods to determine if a meter will mesh into the system. It is necessary that a proper statistics and meshing calculation is done between network element and its potential neighbors so that correct scaling and performance of the network can be achieved.

Once the viable mesh links are derived, it is then possible to look at how the system will behave in terms of its mesh configuration. This configuration will control what capacity constraints may exist in the network.

Applying Capacity Constraints

EDX SignalPro allows the following considerations to be applied to the analysis:

- Minimum link power
- Hopping limits per device type
- Capacity limits per device type

In each layer of the AMI mesh architecture there are potential capacity bottlenecks.

For example, each collector will find itself communicating with a certain number of meters.

Where meter density is high, the collector maximum data throughput can become a limiting factor. In this case, EDX SignalPro informs the designer of where these capacity bottlenecks occur and can also automatically select the proper number of collectors that provide the desired level of capacity for the system.

Load Balancing

It is also desirable to have repeater locations that provide balanced traffic loads through the network. If repeater selections are made that do not provide this balance, a single repeater can easily become the main path for many meters and other repeaters. This would cause a bottleneck in the network architecture and reduce overall performance as well as reducing reliability by setting up a single point of failure. A properly designed and well balanced system will have the appropriate amount of repeaters in the right locations. It is only possible to do this accurately when using a mesh link based modeling approach that considers these capacity constraints.

A Capacity Constrained Design Example

Figure 4 shows the same network as previously analyzed above with the simple coverage-only approach but designed instead using the capacity constrained mesh methodology.

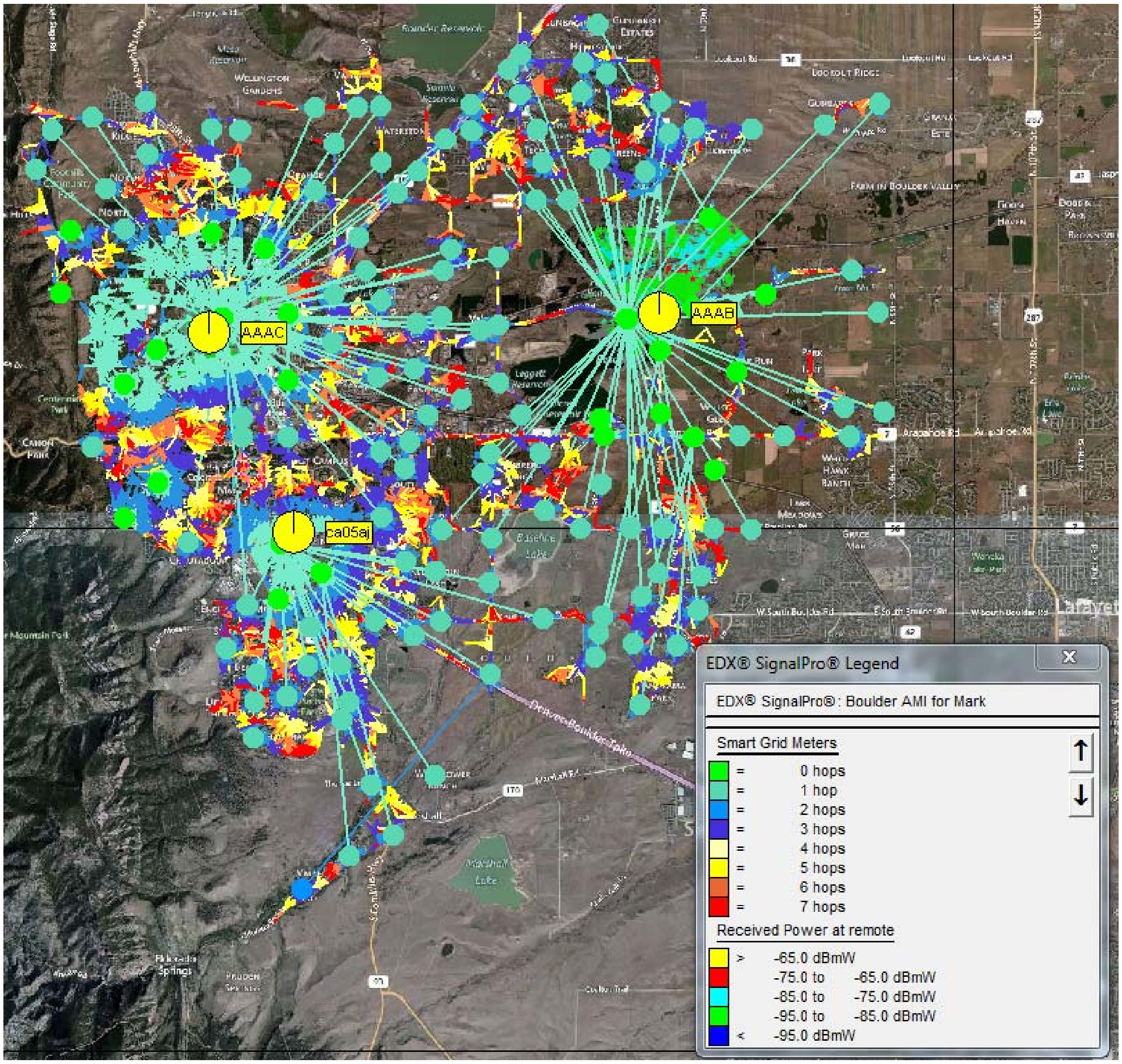

Figure 4: Capacity Constrained Mesh Design

This same meter and collector configuration of 40,000 meters and 3 collectors is now covered with only 150 repeaters versus the 300 repeaters used in the coverage-only based method. This network design respected the geography, the meter density and the capacity constraints of the network elements. This network is using the appropriate number of repeaters to bridge the meters and collectors and accomplishing it with fewer hops at a lower cost.

By comparing the two designs in figures 3 and 4, one can readily identify shorter repeater chains in the capacity constrained approach resulting in lower latency, and better use of meshing to balance load distribution while improving resilience and reliability. Overall network performance and system capacity is thus maximized by using this more sophisticated methodology. This makes the design far more scalable for future expansion.

Effect of RF Link and Noise on Throughput

EDX Advanced Mesh analysis addresses the primary critical question of "can you close the RF link" but then goes on to analyze the effect that capacity constraints have in a real world network. However, it does not examine the complete effect of the RF environment on what actual data rates may be achieved on any particular link. The RF environment is highly complex and cannot be modeled to an entirely complete extent. Some unaccountable propagation conditions may still exist and these RF constraints might further reduce capacity for example, when the link was only able to achieve 16QAM modulation rather than 64QAM. This would limit the maximum capacity of the network to carry data.

It would be useful to develop the capability to model even more completely the RF link and external/internal noise and the effect this has on performance for collectors, repeaters and even meters. Such a capability would help determine areas which work, but are capacity bottlenecks and which may limit performance or future expansion. However, this task is a formidable one from a modeling standpoint. Still, with modeling techniques afforded by tools such as EDX SignalPro one can get very close to an accurate model of the actual network in a fast and cost-effective way. This saves engineering design time and eliminates excessive equipment purchases and reduces deployment effort.

It would also be beneficial to collect RF information from the deployed and operational network and feed this data back into the modeling environment to analyze the effect of interference and noise floor on system capacity. This could provide a way to identify in advance weak or underserved areas as well as providing a roadmap for future network expansion.

These future concepts are under investigation by EDX in conjunction with our users and will likely find their way into a future release of the tool.

Summary

Radio spectrum (channels and bandwidth) is a cost for an RF network. Reliability (or resilience) is also an added cost as it ultimately requires the provisioning of redundant bandwidth. It follows that by optimizing spectrum usage one will optimize cost while maximizing reliability.

The approach outlined in this paper describes an iterative tool-based approach which contemplates the various constraints and costs at each element of a complex system and allows a designer to create an optimal design for a large scale AMI mesh network.

