**Section 6.4 Multi-Link/Multi-Hop/Mesh**

**Background**

Several networking topologies were discussed in Section 4.2.2.4. This section will provide additional discussion of some of these topologies and specifically those more commonly used in the Neighborhood Area Networks (NAN). One definition of a NAN is a common network infrastructure that links multiple intelligent devices in a relatively small or neighborhood sized geographic area. This section will provide a general overview of the NAN and several important considerations for its use in a Smart Grid environment.

Referring to Figure 2 of Section 3 we see the Smart Grid Conceptual Reference Diagram showing the multiple Domains and the network infrastructures interconnecting them. Shown there we see two holistic NAN infrastructures, one identified as a Field Area Network (FAN), and the other identified as an AMI Network. Both the FAN and AMI Networks are each shown as composite but separate networks in this diagram in order to show their relationship and support for two of the Smart Grid Reference Domains. More specifically, the FAN is depicted as supporting and serving the Distribution Domain, and the AMI Network supporting and servicing the Customer Domain. While this depiction is appropriate for the conceptual or high level Domain view of the SG, it is somewhat misleading from the physical network implementation perspective. In actual practice both the FAN and the AMI Networks can and usually are composed of multiple smaller geographically based networks or NANs, each with one or more Data Aggregation Points (DAPs) as will be described in greater detail below. Also depicted in Figure 2 of Section 3, the communication network endpoints for the AMI Network NANs include the 2-Way AMI Meters and ESI – Utility. The endpoints for the FAN and NANs include distribution feeder devices and may also include a FAN Gateway linking with a Substation Network. While Figure 2 of Section 3 illustrates the Domain view of the SG Systems, it should be noted that both the Distribution Domain and Customer Domain will have significant geographic overlap, and thus the network infrastructures serving them likewise will have significant geographic overlap. This overlap leads to the potential for integrating the FAN and AMI Network NANs in these common geographic areas into a common network infrastructure. Thus in these areas, a single composite NAN may be implemented to provide connectivity for the endpoints from both the AMI Network (i.e. the AMI meters) and FAN endpoint devices (i.e. field Distribution Automation devices). Throughout the rest of this section the distinction of the Domains served will be considered only insomuch as the endpoint devices for the Domains will bring different use cases and thereby bring different network requirements. However, the primary focus of this section will be on the underlying NAN infrastructure and considerations for supporting the uses cases for the various end devices served by it.

The subsections below will cover the components of the NAN in greater detail but a common network element of the NAN is the Data Aggregation Point (DAP), as mentioned above. While the different AMI and NAN vendors typically identify the DAP using their own specific product names, the primary purpose of the DAP is to serve as a gateway from the NAN to other networks to ultimately link back to one or more common application system and services. In some cases more sophisticated NANs allow more than one DAP for an individual NAN that may allow segregation of traffic types and may allow linking with different upstream application systems. Other commonalities and distinctions will be discussed further in the following subsections considering the technology and topology of the NAN.

Furthermore, for the current Smart Grid implementations the dominate use of the NAN is for AMI. In these implementations the NAN provides connectivity between AMI meters and a DAP, with the DAP having a backhaul communications path to the host AMI System or AMI Head-End. For these dedicated AMI system there are specific requirements for information flow between the back-office metering systems, through the NAN, and to the individual AMI meters. For these AMI systems, there is no need for the meters to share their metering information amongst themselves, but only to share this information with the AMI Head-End and the centralized metering system. Therefore meter to meter (i.e. peer-to-peer) information sharing in the NAN is not required. However, in a Multi-Hop AMI NAN the meter communication modules may be called on to relay messages between the DAP and other meters too far removed from the DAP to directly link with it and they may also exchange network housekeeping messages between the communication modules of neighboring AMI meters. As these AMI NAN networks are expanded to include DA devices there may be additional requirements for the NAN to support direct peer-to-peer information exchanges between these DA devices leading to additional requirement for the NAN to support these peer-to-peer routes along with effectively managing message priorities. Both the current and potential future requirements of the NAN should be fully considered when choosing a technology and topology for NAN connectivity.

**6.4.1 Network Topology Revisited**

In order to better identify the common NAN infrastructure a brief digression further into network topology is in order. Multiple terms are often used in conjunction with the NAN; Multi-Link, Multi-Hop, and Mesh. However, these terms may be misleading and it can be said may inaccurately describe the commonly deployed NAN topologies.

The term Multi-Link network can be defined as interconnecting multiple discrete networks, such as linking a HAN with a NAN, then to a WAN. The obvious reason for interconnecting these networks is to allow data exchanges between the devices connected to these discrete networks. That is, a Multi-Link network path can be established through the linked HAN, NAN, and WAN Multi-Linked networks.

The term Multi-Hop network can be defined as group of interconnected nodes in a common network infrastructure where links to traverse this network can be established by using node-to-node or hop-to-hop links, thus the term Multi-Hop.

The term Mesh is used to describe a family of interconnected nodes in a common network infrastructure. There are several forms of mesh topologies which are well documented in multiple books and other technical papers on network systems. However, briefly here, the term full mesh is commonly used to describe a mesh where each node is directly connected to each other node, which can lead to an inordinately large number of links in large networks but also provides the largest number of direct communication paths. With a larger set of links, a full mesh has more choices to dynamically adapt to faults or traffic loads in any given communication link. A partial mesh is a subset of a full mesh where not all nodes are directly linked to all other nodes, and traversing the network may involve relaying or routing through multiple nodes or in essence forming a Multi-Hop link.

The goal of a classical mesh network is to provide connectivity from any node to any other node. However, in an AMI NAN, the application level or “use case” data is usually limited to exchanges between the DAP and the AMI meter. Stated another way, within the AMI NAN the community of interest is between the DAP and the individual AMI meters with one being considered the source and the other being considered the destination or sync of the data. Thus for an AMI NAN, the goal is to provide links from a DAP to the AMI meters. A potential exception to this DAP to end device community of interest within a NAN may be if DA devices are linked via the NAN and the DA applications or use cases require some peer-to-peer data exchanges between the DA devices. Node-to-node data exchanges for AMI NANs are otherwise generally limited to network housekeeping messages where the AMI meter communication modules share information amongst themselves on link and network status and best routes. However, it should be obvious in Multi-hop AMI NANs the meter communication modules will often be used as relay points to relay messages between the DAP and other AMI meters further downstream.

As indicated in Section 4.2.2.4 the nodes in a Multi-Hop NAN are typically intelligent devices (endpoints), that have the ability to discover (multi-hop) forwarding paths in the network and make their own forwarding decisions based on various pre-configured constraints and requirements. Using this dynamic routing capability, the endpoints first determine which neighbor nodes are within radio range, assess potential links with these neighbors and dynamically choose the best or most appropriate path as their primary route through the NAN to an DAP. Depending on the routing algorithms implemented in the endpoint nodes, this best route determination may be based on RF signal strength, ability to exchange messages with neighbor nodes with minimal errors, using neighbors that provide the minimum number of hops back to an DAP, the geographic coordinates of the nodes, or a combination of the these. The subject of routing and route determination algorithms for wireless Multi-Hop networks has been the subject of study for many years and multiple books and other publications are available on this subject. Suffice it say here the meter nodes will use their programmed algorithms to select what they have determined as the best route back to a DAP at that particular point in time. It has been noted that some of the dynamic self configuration algorithms implemented in currently deployed NAN networks may occasionally lead to unstable or otherwise infeasible routes and may need some external oversight to force a usable route or the additional of other NAN network devices to establish useful routes.

In addition to selecting a primary path and route to a DAP, an AMI meter node will typically also preselect other (second best) routes to be used should its primary route become degraded or unavailable. Normally all AMI meter traffic to and from a DAP will use only their currently established primary path. The secondary path would be used if and when it is promoted to be the primary path because the previous primary path had degraded or become unserviceable.

An interesting side note is that while the NAN AMI meter nodes have the ability to link with any of their neighboring nodes (within RF range) and potentially route through them, in practice as the routes are established between the DAP and the AMI meters, the routes usually form a “tree” network structure. For an AMI NAN this is a consequence of the need and requirement that the AMI meters exchange information only with their selected DAP, using the Multi-Hop links through other AMI meter nodes merely as relay or routing points. In this tree structure the primary branches or links extend from the DAP to a first layer of nodes and from this first layer of nodes additional branches or link extend to secondary nodes, and so on until all nodes have established a path between themselves and the DAP. The distribution of the number of hops from the end nodes to the DAP is then a general index of how effective the NAN may be in providing connectivity to the devices in that NAN. The nodes further removed from the DAP having a greater number of hops to traverse will also have greater latency and are generally more susceptible to having their path to the DAP interrupted as propagation conditions in the NAN may change.



Figure 1

Finally, while the AMI NAN is often described as an AMI Mesh, in reality most AMI NANs used to establish connectivity between the DAP and the AMI meters are using Multi-Hop links simply to relay messages between the DAP and the meter. Thus the routed links in an AMI NAN usually form into a tree network structure and using the term mesh to describe this network, while not totally inaccurate, is generally misleading regarding the data carrying network structure established in the NAN. It is worth mentioning for an AMI NAN that even though the nodes attempt to establish the best path back to a DAP, and thereby form a tree structure, often the NAN nodes will also preselect other (or second best) neighboring nodes to link with should its link with the currently selected next hop node in the route to the DAP become unavailable. An important consideration for a Multi-Hop NAN is its ability to dynamically adapt to communication link faults by utilizing alternative branches from the Multi-Hop link possibilities.

**6.4.2 The NAN in a Larger Context**

Another concept is the use of the term AMI Network or mesh to describe a single monolithic network spanning large geographic areas. However, an individual NAN infrastructure will consist of at least one DAP and a number of endpoint nodes or meters linked to it, and potentially other relaying/routing devices to extend the reach of the NAN or to provide additional reliability. Thus the term AMI Network while generally used to connote a single monolithic network is in reality an aggregation of multiple individual NANs, each consisting of a DAP and the end nodes connected to and through it. These multiple individual NANs collectively provide coverage and connectivity to the end nodes in larger geographic area. However, this is not to say the individual NANs operate totally autonomously and independent of each other. As several DAPs are deployed in a geographic area, the AMI meters in this area will use dynamic routing to establish the best route to a DAP, which in some cases may not be the geographically closest DAP. In reviewing the links established in working AMI NAN networks, it is often observed there are significant areas where individual meters in common geographical areas establish links to different DAPs. One of the obvious advantages to this is the potential redundancy offered in areas with multiple DAPs. If one DAP fails, or the backhaul link serving it fails, the meters normally served by that failed DAP can and will dynamically reroute to link with other meters connected to other working DAPs. An example of this is shown in Figure 2a.



Figure 2a

In addition to rerouting to bypass a failed DAP the individual nodes have the ability to dynamically reroute within the NAN should the path currently chosen as their primary route to the DAP become unavailable or unreliable. In this case, the node will typically try to route through its preselected second best route, or if that also fails, the node will continue to evaluate neighbor links to find the best route back to an DAP. An example of this is shown in Figure 2b.



Figure 2b

Similarly if an intra-NAN link fails, the nodes that were supported through that failed link will reroute to establish a new path to a DAP. An example of this is shown in Figure 2c. However, in this example note the new route chosen is to a different DAP only because that new route may have been determined as the ”best” route to a DAP during the route recovery process.



**Figure 2c**

**6.4.3 Other NAN Topologies**

While the focus of this section is on the AMI Multi-Hop network topologies it is worth mentioning some other alternatives commonly used to provide connectivity between AMI meters and the AMI host or AMI Head-End system.

One example of this is the use commercial or private cellular like networks to establish point-to-multipoint links from a master radio site or base station to the endpoint devices. While the commercial cellular networks are designed and deployed primarily to support mobile devices moving from cell to cell, they can and do also serve fixed devices like the AMI meters. In these systems, each base station typically serves smaller geographic areas but are generally deployed in order to provide overlapping coverage serving larger geographic areas. Utilizing commercial cellular services for linking with AMI meters may be appropriate in areas where implementing private or purpose built wireless network are not feasible or are not cost effective. These are described in some detail in other sections.

Other AMI systems may use purpose built point-to-multipoint wireless networks designed specifically to support fixed locations. As such they can be implemented without the additional complication of tracking and handing off mobile devices as they move from cell to cell. These are generally tower based systems and are typically designed to provide connectivity extending multiple miles to remote AMI meters. Therefore a single master radio or base station may be able to provide coverage over a large geographic area.

In both point-to-multipoint networks described above, the master radio or base station would then be linked through an appropriate backhaul network to a centralized AMI system or host.

Point-to-multipont networks may be implemented to cover different geographic areas ranging from Pico cells covering tens to hundreds of feet across to Mega cells covering areas hundreds of miles across. Pico cells might be appropriate in small geographic areas like meter closets in multiple dwelling units, where satellite based Mega cells might be appropriate in linking with multiple highly remote meters spread over large geographic areas ranging up to hundreds of miles across. Use of these technologies should be considered when the use of other primary technologies may not provide effective coverage for all meters in a service territory. Several example implementations are shown in Figure 3.



Figure 3

**6.4.4 NAN Network Components**

This section identifies some of the network elements commonly used in implementing NAN systems.

One of the original purposes of the NAN was to provide network connectivity from a centralized metering system to remote AMI meters, thus the original name AMI NAN. Using the network connections, the centralized metering system was able to retrieve energy usage and other information from the AMI meters and to send configuration and other command and control functions to them.

Typical AMI NAN implementations also included a centralized AMI Head-End management system linked to the NAN through a backhaul network to provide network management and control of the NAN elements themselves. This AMI Head-End system is depicted in network diagram Figure 2 of Section 3..

As for the NAN nodes themselves, to some extent the type and function of these nodes are dependent on the technology and topology used to implement the NAN. However, there are some elemental components commonly used in these nodes. For wireless NANs, one of the elemental components of a node is a NAN radio. The NAN radio is typically modularized and will consist of a RF transmitter and receiver, antenna, and the control electronics which allow the radio (and thus the node) to actively participate in the NAN. NAN radios are mated with end devices, for example, AMI meters, DA devices, etc., typically in a composite package provided by the OEM or end device manufacturer. For AMI meters, this package is almost always in the meter housing itself or “under cover”. In any case, the NAN radio provides a data interface used to interconnect with the meter or other end device. Other NAN radios may be implemented as standalone repeaters, relays, or routers used to strengthen and/or extend the reach of the NAN. Also common to wireless NAN systems are the DAPs. The DAP serves as the centralized connection point for its supported NAN nodes and thus will include one or more NAN radios to link with these nodes. The DAP will also contain a backhaul network interface and necessary controlling electronics to allow it to be linked with the NAN Head-End through a backhaul network.

Depending on the vendor and NAN networking technology used, the NAN radio module may also be capable of supporting additional data processing functions as may be required to properly interface with its connected end device. This data processing capability may be necessary to aggregate end device data for more efficient network transmission thought the NAN or to accommodate specific application level or native protocols utilized by that end device.

**6.4.5 Characteristics of NAN Multi-Hop Networks**

In evaluating the use of Multi-Hop NAN networks the following are some of the major elements and characteristics to be considered.

* Intended use of the Network – AMI only, DA, HAN Interconnectivity, Direct Load Control, or a combination of these. The applications and use cases, both current and those projected for the future should be considered carefully when establishing NAN requirements and evaluating NAN capabilities.
* Size of the Network – Consideration must be given to the number of end devices, their function, their location, their density, and the variability of their density.
* Geographic location and RF morphology – The terrain and other RF environmental factors that could impact the reach and reliability of the NAN for each geographic area should be considered.
* Bandwidth Requirements – Consideration for deterministic and non-deterministic traffic, average and bursty traffic patterns, and the relationship of the traffic patterns with latency requirements.
* Node Throughput – Consideration for the processing power and packet throughput capacity of the NAN device nodes, repeater nodes, and the DAPs
* Latency Requirements – Each application and use case may bring additional latency requirements. In a Multi-Hop NAN, latency can be significantly impacted by several factors including the node-to-node effective data throughput rate (which is in turn related to RF bandwidth, RF modulation efficiency, and error rates) and the internal processing delay introduced by intermediate nodes in relaying data packets. Consideration should be given to the distribution of the number of intervening nodes or hops that may exist between the DAP and nodes in that NAN. The cumulative or combined latency of multiple hops encountered in reaching end nodes further removed from the DAP may be significant.
* Growth Potential – Both in number of end nodes and functionality.
* Resiliency and Redundancy – Requirements for recovery of failed network elements along with the techniques employed to provide redundancy.
* Security – Security requirements for joining the network, preventing unauthorized attachment or connections, and permitting data exchanges between authorized nodes
* Backhaul requirements and availability – The requirements of the backhaul links from the NAN DAPs to the centralized systems, and the availability of these backhaul links. Of particular importance here is the additional latency or any capacity constraints that may be introduced by the Backhaul component of the network.
* Ease of Deployment Potential – How capable or flexible does the Network need to be to adjust to the deployment planning, processes, and physical environments.

**6.4.6 Additional Technical Characteristics of the NAN**

Several vendors offer NAN systems designed to support AMI and other SG data requirements. While most of these employ the use of Mesh or Multi-Hop networks as described in this section, they can vary significantly with respect to their implementation.

Several technical issues to consider when selecting a technology, topology, and vendor include the following:

* Spectrum Used – Many commercial AMI NAN systems use the 900 MHz (902-928 MHz) Industrial Scientific and Medical (ISM) band. Others use the 2.4 GHz ISM bands. These bands are unlicensed, and with some technical restrictions on their use, they are shared by multiple users. Other systems use private licensed frequencies, thus minimizing potential interference with shared users. Still others may use the registered but non- exclusive 3.65 GHz band. Regardless of the spectrum used, the capabilities and limitations inherent with this spectrum should be considered in choosing a NAN technology and topology. A number of other sections provide much more information on the capabilities and restrictions of the spectrum choice.
* Route Forming and Maintenance – As a NAN, that is a DAP and associated end devices, form a mesh or Multi-Hop network, a set of data paths or routes will be established from the end devices to the DAP. These routes will form as a result of the dynamic self routing ability inherent in the nodes of the NAN. As indicated in Section 4.2.2.4 the nodes in a Multi-Hop NAN are typically intelligent devices that have the ability to discover (multi-hop) forwarding paths in the network and make their own forwarding decisions based on various pre-configured constraints and requirements.

Consideration should be given to the length of time it takes to initially form and stabilize the routes, how often and under what conditions automatic route maintenance (i.e. the process of analyzing network performance data and automatically performing node-to-node incremental network tuning) is performed, as well as routing recovery time for internal NAN node failures.

Another important consideration is the ability of the NAN nodes to route to an alternate DAP should a node’s primary DAP fail. Yet another important consideration is the ability of a NAN to recover after a significant widespread power outage. The ability of the nodes to hold their current configuration and routes in non-volatile memory would offer a significant advantage for quickly restoring operation after power is restored, although some network “churn” may be expected as the nodes are repowered and begin to return to normal operation.

Related to these automatic routine process is the possibility that due to the long lasting loss of end device nodes or any long lasting changes in the RF environment in an area may necessitate a manual redesign process including the relocation or addition of the DAPs, repeaters, relays, or routers.

* NAN Throughput – Its capability to support the volume and latency requirements for data exchanges from the DAP to the end nodes. This is, in turn, related to multiple technical aspects and operational processes used by the DAP and other NAN nodes. The DAP must support the interconnection with the Backhaul network, the links with its internal NAN nodes, and process and relay all data to and from all of the DAP’s attached NAN nodes. The internal NAN nodes must relay data for its supported downstream nodes and also process all data exchanges between itself and the DAP. Considerations should be given to the following technical aspects:
  + The processing power of the DAP
  + Number of discrete radios in an DAP
  + Processing power of the internal NAN nodes
  + The bandwidth of the NAN radio links
  + The RF modulation scheme used
  + The hop-to-hop latency
  + Data fidelity checks and recovery processes used in the NAN

Equally important to these technical aspects is the degree to which the NAN technology is conforming or adhering to the Standards being fostered and promulgated by the SGIP in the Catalog of Standards (CoS). For greater detail of the technical aspects, multiple books and technical papers have been written on these subjects. Suffice it to say here these are important items to be fully considered in selecting a NAN infrastructure.

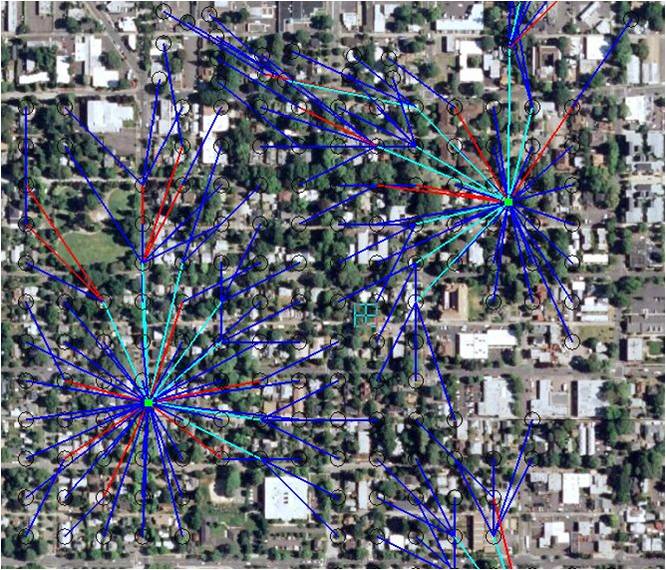
**6.4.7 Further Considerations for NAN Design and Routing**

This sub-section addresses some of the complications that would be encountered in designing Multi-Hop NANs.

As indicated in this section, a Multi-Hop NAN generally will be self forming by the nodes themselves using dynamic routing algorithms. To use standard RF modeling techniques to predict the optimal routes that would be formed in a NAN and then predict the operation characteristics of the combined links and routes for each NAN node would be a formidable task. Consider that the number of nodes or AMI meters in a NAN and linked through a single DAP may be in the order of thousands, and as a result, there may tens of thousands of candidate RF links that would need be modeled and evaluated to determine an optimal connectivity path or route from each internal NAN node to the DAP. Further complicating this exercise would be the recognition that a NAN will be in a dynamic RF environment. Considering that nodes are subject to being added or removed, obstructions such as vehicles changing locations, changing weather conditions, vegetation changes throughout the year, etc. the NAN will always be in some state of flux as it dynamically adapts to the changing environment. To model this environment would be an extremely difficult task when using discrete RF modeling techniques as may be used in modeling point-to-multipoint network links as described in Section 5. Considering the sheer number of point-to-point links possible in a Multi-Hop NAN network consisting of thousands of relatively closely located end nodes make this an almost impossible task. In summary, each individual link has associated with it a specific probability, at any given time, a satisfactory connection will be achieved; that is to say having a received signal above threshold, it is a daunting task to come up with an easy-to-use mathematical model to analyze and accurately predict the routing within a NAN.

Even with the difficulties identified above, most vendors supplying AMI meters and/or the Multi-Hop networks to support them have typically developed a set of internal tools and capabilities to assist them in developing effective and efficient Multi-Hop NANs. Given the number and location of the AMI meters or other end points to be covered, they use these internal tools along with knowledge of the terrain, clutter, and other characteristics for a particular geographic area, combined with “rules-of-thumb” they have developed while implementing previous NAN systems to produce the infrastructure designs. Using techniques and process they have found to be successful allows them to predict with some degree of accuracy the number and placement of the DAPs and RF repeaters or relays or routers required to effectively service the specified number and location of the AMI meters or other end nodes. It is worth noting these vendors may also have internal simulation tools to validate their designs prior to implementation. However, it would be prudent and indeed necessary to validate expected performance of the NAN after implementation in the field and to augment or adjust infrastructure if necessary to achieve required performance.

Finally, there are some evolving commercial available RF software modeling tools specifically designed for designing and analyzing Multi-Hop NANs. These tools use the proposed number and location of the AMI meters or endpoint devices to be included in the NAN, along with some NAN design constraints (for example the maximum number of hops allowed from an end node to the DAP) to develop an infrastructure designs. These tool take into account the combined RF coverage that would be provided by the proposed infrastructure devices (DAPs, relays, repeaters, and routers) along with the additional RF coverage that will be provided by the end nodes themselves to propose an infrastructure design which would include the predicted routes the AMI meters or other end nodes will form when linking back to the DAP. These tools allow a designer to specify design constrains like load and maximum hop counts allowed within the NAN. However, the routes formed within a NAN when deployed in the field will likely not exactly match the predicted configuration for the same reasons mention above relating to the dynamics of the RF environment in a given area. Never the less, the proposed infrastructure design should enable the formation of a Multi-Hop NAN suitable for providing effective and reliable connections of the NAN end nodes with the DAP. As one might expect, these tools are extremely process intensive and may require multiprocessor computing power to develop designs within a reasonable amount of time for large numbers of end devices covering large geographic areas. An example of a several relatively small NAN designs and their predicted links or routes is shown in the figure below.



**Figure 4: Example NAN Design from Software Design Tool**