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How to Properly Design an In-Building DAS

Part I: Use of Directional Couplers in DAS

by Minfei Leng

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Introduction

RF in-building coverage has become a fast growing market in recent years. Commercial wireless users increasingly demand reliable communications inside office and residential buildings for their business and personal needs. At the same time, various local municipalities have issued ordinances to ensure that construction of new buildings include adequate radio coverage of public safety signals. Efforts are also underway to develop and implement national level model codes for public safety in-building communications, as seen by recent initiatives at National Fire Protection Association (NFPA) and the International Code Council (ICC).

A typical in-building coverage system consists of two major components, a bi-directional amplifier (BDA, or signal booster) relaying and amplifying the RF signal traffic between the remote base station and the portable or mobile radios, and a network to distribute the signal to every corner of the desired coverage area.

The most common type of the distribution network is a system of coax cables and indoor antennas called a Distributed Antenna System or DAS.

Most of the reference materials and application notes on in-building coverage solutions have focused on the booster technologies or system design architecture. One often overlooked aspect in the system design is the DAS implementation. This includes connecting all the cables and antennas throughout the building and balancing the signal levels at each DAS node. If ignored, an improperly designed DAS results in degraded performance and unnecessary cost increases. This 2-part series of articles is an effort to outline a simple process of designing a DAS in order to achieve the most efficient RF coverage distribution. Part I talks about the Use of Directional Couplers in DAS and Part II covers the DAS Design Process.

Part I: Use of Directional Couplers in DAS

When facing the question of cable connections in a DAS, many designers or installers choose the easy answer of using standard two-way splitters for every cable and antenna junction. The splitters are relatively inexpensive, and there is no thinking required. However, except for the simplest systems with very small coverage area and few antennas, the use of splitters will have a seriously negative impact on the system performance.

Let's look at an example. It's a very simple DAS with five antennas. All cable splits and antenna junctions are connected with two-way splitters. Each splitter provides a 50%-50% split of the power, which translates to a 3 dB insertion loss between the input port and the two output ports.

The splitters are bi-directional, so when two signals are combined through the splitter going the other way, there is also a 3 dB insertion loss.

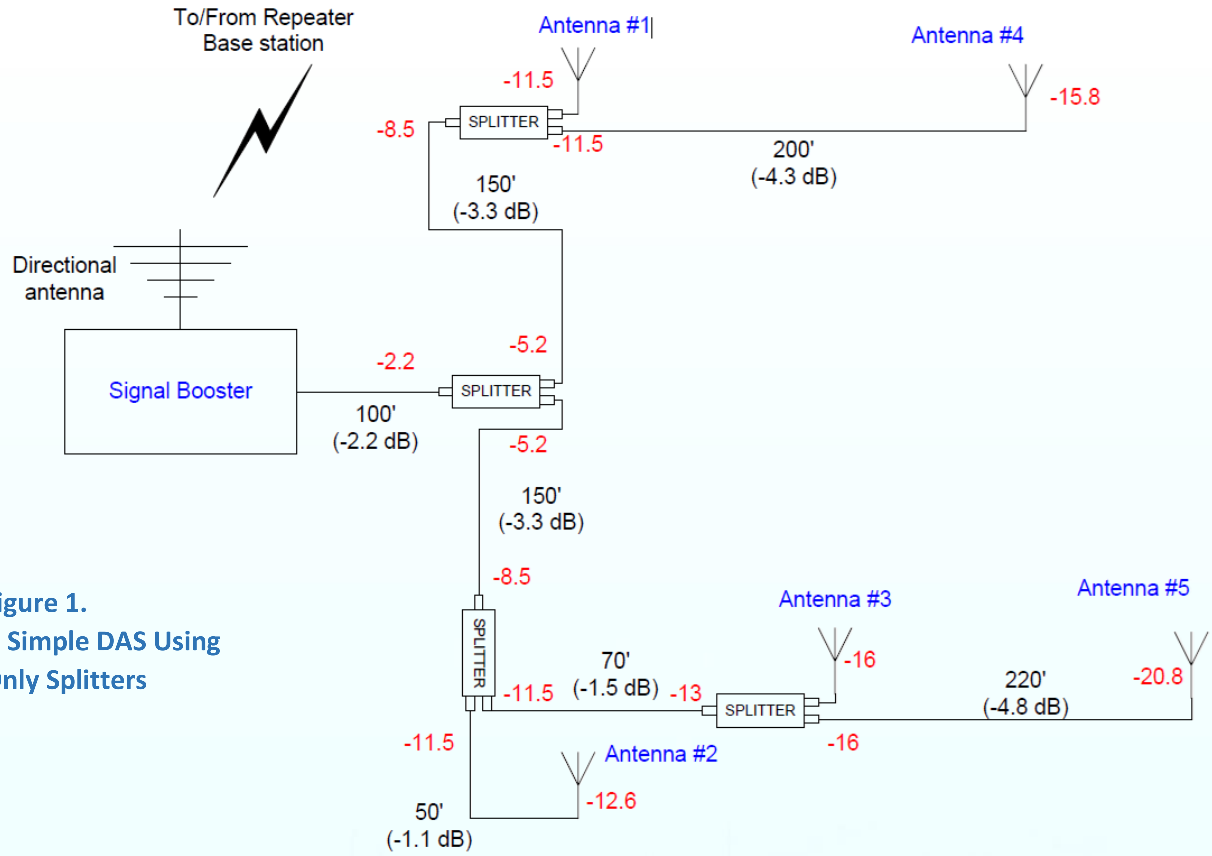
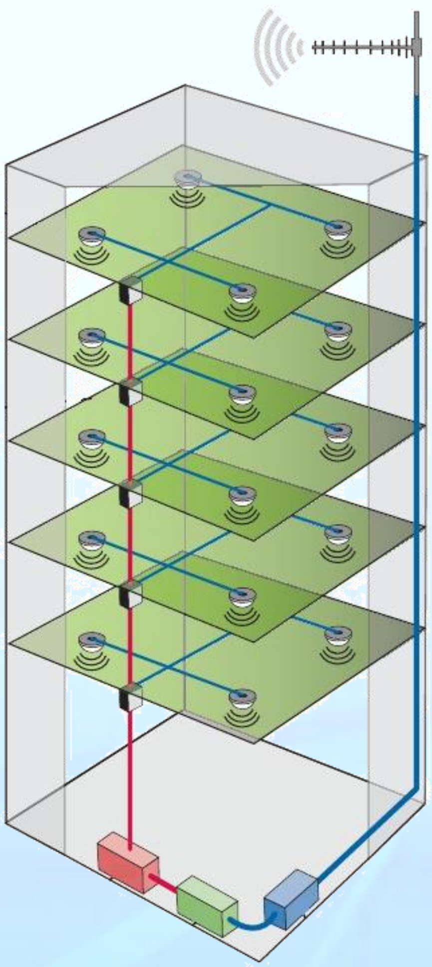


Figure 1.
A Simple DAS Using Only Splitters

The red numbers shown in Figure 1 are cumulative losses, expressed in dB, in reference to the output of the Signal Booster. If we assume the signal coming out of the booster is at 0 dBm, then the numbers can be viewed as signal levels at each junction expressed in dBm. It is obvious that the signal levels at the antennas vary quite a bit. The signal levels at Antennas #1 and #2, which are nearest to the booster, are -11.5 and -12.6 dBm, while the signal level at Antenna #5, farthest away from the booster, is -20.8 dBm. There is more than 9 dB of difference between the near and far antennas. With increased size of the DAS and the number of cable splits this “near/far” problem is even more serious. In a more typical DAS, instead of a simplified example as shown above, it is not uncommon to see signal level differentials of more than 20 or 30 dB!

Such a scenario can lead to severe degradation of the in-building coverage. When antenna nodes in the DAS have equalized losses, the most uniform coverage is achieved, i.e. portables anywhere in the coverage area "sound" the same. Whereas, such disparate signal levels can lead to uneven and diminished coverage both in area size and in audio quality. In extreme cases, calls may even be dropped. Imagine two users in the building: one is positioned at Antenna #1 while the other is at Antenna #5. They simultaneously key up their radios and try to talk back to the central station. If they both use the same radios and are transmitting at the same power level, the signal received from the user at Antenna #1 is simply 9 dB stronger than the one at Antenna #5. If the user at Antenna #1 happens to use a higher power radio, for instance a mobile instead of a portable, his strong signal may activate the Output Level Control in the booster, which is a mechanism used by the signal booster to adjust the gain and output power per carrier based on the strength of the incoming signals. (All boosters have to be equipped with OLC in order to comply with FCC regulation to reduce undesired spurious emissions.) Once the OLC is engaged, it reduces the overall gain of the booster, which further weakens the signal from Antenna #5. Therefore the difference in signal levels between the two incoming signals increases, and the user with the weaker signal will, most likely, not be able to complete his call.



Additionally, to maintain a sufficient signal to noise ratio, the loss in any DAS should be limited to within 25~30 dB. In expanding the example above, there is another hallway beyond Antenna #5 that requires coverage. It needs more cables and splitters so; the loss on that branch will easily go beyond the 25 dB limit. In-line boosters will need to be deployed to amplify the signals when loss exceeds that limit.

Since the signal levels at Antennas #1 and #2 are unnecessarily high, it would be more efficient if we could divert some of the RF energy away from Antennas #1 and #2 and send them toward #5. In other words, as the signal comes out of the booster, what if we provide only a small portion of the signal to the shorter branches, but preserve the majority of the RF energy for the long run toward Antenna #5? We can accomplish that with Directional Couplers. A 2-way splitter is a simple 3-port device, forming a physical and a functional "Y", a Directional Coupler is typically a 4-port device.

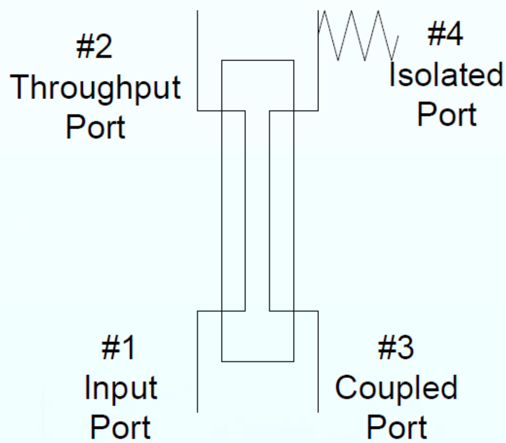


Figure 2.
Example of a Typical
Directional Coupler Schematic

As shown in Figure 2, right, the four ports on the coupler have different designations depending on the signal path. When used in a DAS, one of the ports will have a load connected to it. The use of this port will become evident shortly when we discuss the bi-directional nature of the coupler. When a signal enters the coupler from the #1 Input Port, part of it comes out from the #2 Throughput Port (sometimes called ThruLine Port) and another part of the signal comes out from the #3 Coupled Port (sometimes called Decoupled Port). The ratio between the signals is commonly referred to as the "coupling ratio" and is usually noted in dB. If the ratio is 3/3 dB, then the two signals are split 1:1 evenly and each output is 3dB lower than the input signal. But the coupler can also be constructed to have uneven split ratio. Let's look at an example of a 4.8/1.8 dB coupler, which has a 1:2 split ratio, or in other words, 33/66% of the input signal.

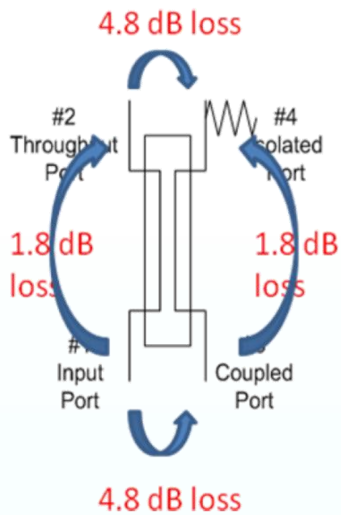


Figure 3.
A 4.8/1.8 dB Coupler

As shown in Figure 3, compared to the input signal, the output at the Throughput Port is 1.8 dB lower than the input signal, while the output at the Coupled Port is 4.8 dB lower.

However, the designations of the ports are not fixed since the coupler itself is symmetrical. In reality, a RF signal can enter any port. Whichever port you select as the Input, the other port on the same side becomes the Throughput Port, while the port opposite side from the input becomes the Coupled Port. As shown in Figure 4, if the signal is now coming in from Port 2, which is now designated as the Input Port, then we simply have a whole new set of port designations noted in red.

Please notice that nothing has changed physically between Figure 3 and Figure 4. The load is still on Port #4. The only change is in the reference point or the perspective of the "input" port. Remember the signal booster and DAS are bi-directional by nature, so another way to look at these two figures is that the coupler in Figures 3 and 4 is seen from the perspectives of opposite signal paths (uplink and downlink). In Figure 3, it's the downlink signal that goes from the booster out to the DAS antenna node. In Figure 4, the signal from the portable radio is picked up by the in-building antenna and is going back toward the booster. In the case of Figure 4, the signal entering Port #2 will have 1.8 dB loss when coming out of Port #1.

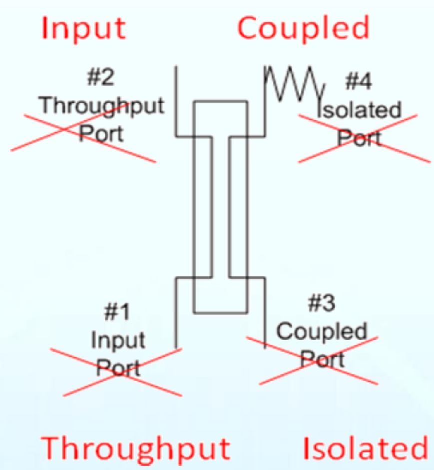


Figure 4.
The Same 4.8/1.8 Coupler with Signal Coming In From Port #2

Another signal at -4.8 dB will go toward Port #4 where the energy is absorbed by the load. Similarly, another uplink signal from the portable radio back toward the booster enters the booster from Port #3 (marked as the Coupled Port in Figure 3). It loses 4.8 dB and comes out of Port #1 as well.

Some of that signal goes to Port #4 at -1.8 dB and is also absorbed by the load. Hence, the signal paths between Ports #1 and #2, and Ports #1 and #3 have the same loss in both directions. Such bi-directionality and fixed loss ratio between ports ensure the DAS can be balanced simultaneously for uplink and downlink signals.

Because of this bi-directionality, it's crucial to make the correct port connections during installation. A reversed connection will not be immediately obvious, as the signals will still come through, albeit with very different losses as the designer had intended. It is not unusual for a DAS system to fail the coverage acceptance test even though the design has plenty of margin built-in. The painstaking trouble-shooting process would eventually lead to one or several couplers with reversed cable connections. A simple yet effective way to ensure that the right cable is going with the right coupler port is to have the field technicians hold the coupler with the load oriented in the same way as shown on the schematic. Then the rest of the ports simply fall into place by matching the various cable segments on the DAS layout drawing.

An additional advantage of the coupler over the splitter is the isolation between two ports at the opposite corners (Ports #1 and #4, Ports #2 and #3). Such isolation becomes instrumental in other applications of the directional coupler, such as in a transmit combiner. However, that is not the focus of this white paper.

Beyond the 3/3 dB and 4.8/1.8 dB ratios, couplers can be made to have coupling ratios of 6.0/1.2 dB (25/75%), 7.0/1.0 dB (20/80%), and all the way to 30/0.1 dB (0.1/99.9%). Typically, a manufacturer will offer a series of couplers with varying split ratios for an entire frequency band. Some manufacturers even take advantage of the nature of multiple harmonics and offer couplers that cover VHF, UHF, and 800 MHz frequencies simultaneously. Table 1 on the next page shows the "TXRX Systems" brand coupler portfolio offered by Bird Technologies Group.

Now, let's take another look at the earlier using directional Couplers instead of splitters.

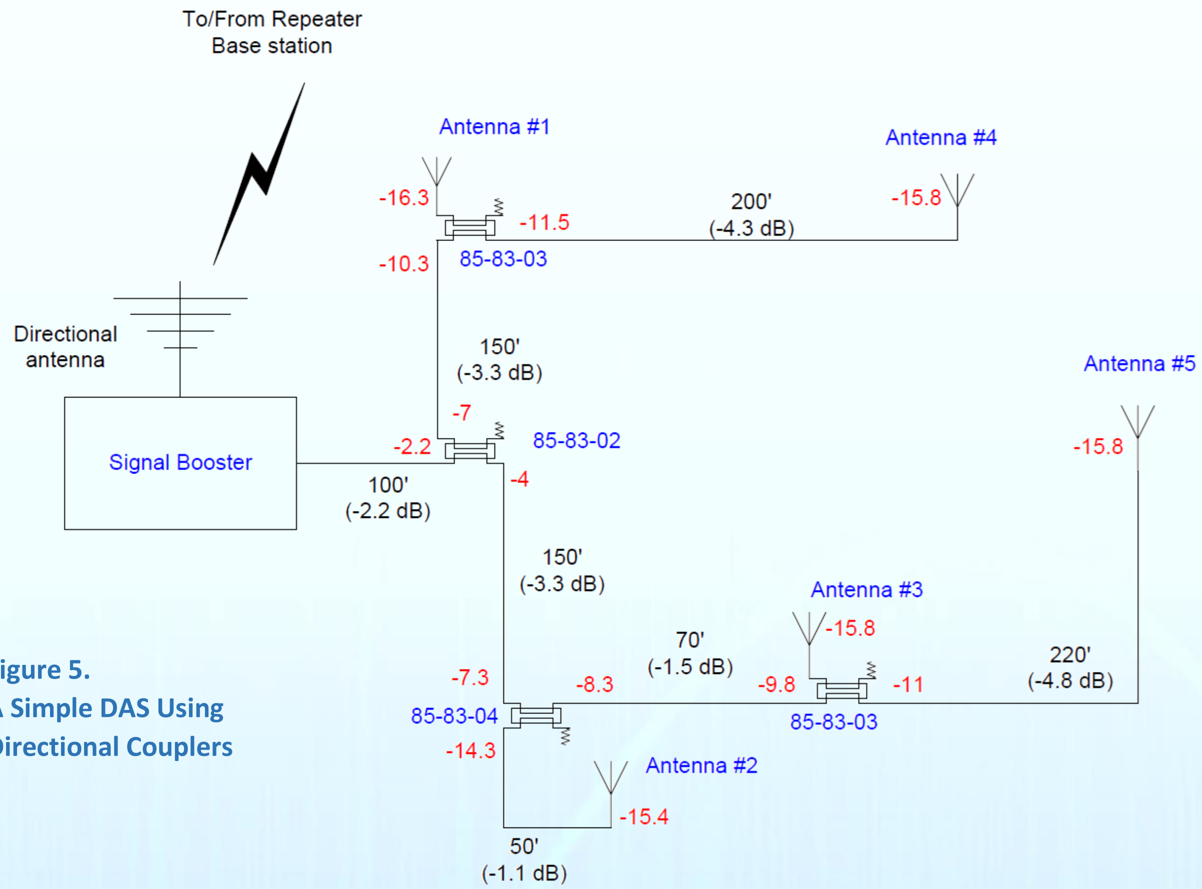


Figure 5. A Simple DAS Using Directional Couplers

With directional couplers, every antenna's signal level is now within 1 dB of each other. We don't need to worry about the "near-far" problem anymore. Nor do we have to spend additional money to install an in-line booster, since the loss of 15.8 dB at Antenna #5 is far below our threshold of 25~30 dB. Therefore, the judicious use of directional couplers greatly improved the system performance by balancing the DAS loss at each antenna node, and reduced the hardware cost by eliminating the need for an in-line booster.

In summary, while the choices of signal boosters and antennas are often the focus of the designer and the user of an in-building coverage system, the directional couplers are equally critical in their contribution to the successful implementation of the DAS.

If you are wondering how to select the correct couplers with the correct split ratios to end up with the balanced signal levels as shown, please see Part II of this article. We will provide a step by step instruction on the DAS design, including how to calculate cumulative losses and how to choose directional couplers in order to balance the signal levels.

Table 1
Directional Couplers

Model Number	**Frequency Band (MHz)**	**Coupled / Through put port Loss**	**Split Ratio in %**
Multi-band Harmonic couplers			
85-05-01	144-174/450-530/806-890	3.0/3.0 dB	50/50%
85-05-02	144-174/450-530/806-890	4.8/1.8 dB	33/66%
85-05-03	144-174/450-530/806-890	6.0/1.2 dB	25/75%
85-05-04	144-174/450-530/806-890	7.0/1.0 dB	20/80%
85-05-05	144-174/450-530/806-890	10/0.5 dB	10/90%
85-05-06	144-174/450-530/806-890	15/0.2 dB	3/97%
85-05-07	144-174/450-530/806-890	20/0.1 dB	1/99%
VHF couplers			
85-38-01	132-174	3.0/3.0 dB	50/50%
85-38-02	132-174	4.8/1.8 dB	33/66%
85-38-03	132-174	6.0/1.2 dB	25/75%
85-38-04	132-174	7.0/1.0 dB	20/80%
85-38-05	132-174	10/0.5 dB	10/90%
UHF couplers			
85-58-01	350-512	3.0/3.0 dB	50/50%
85-58-02	350-512	4.8/1.8 dB	33/66%
85-58-03	350-512	6.0/1.2 dB	25/75%
85-58-04	350-512	7.0/1.0 dB	20/80%
85-58-05	350-512	10/0.5 dB	10/90%
85-58-06	350-512	15/0.2 dB	3/97%
85-58-07	350-512	20/0.1 dB	1/99%
85-58-08	350-512	30/0.1 dB	0.1/99.9%
700/800/900MHz couplers			
85-83-01	746-960	3.0/3.0 dB	50/50%
85-83-02	746-960	4.8/1.8 dB	33/66%
85-83-03	746-960	6.0/1.2 dB	25/75%
85-83-04	746-960	7.0/1.0 dB	20/80%
85-83-05	746-960	10/0.5 dB	10/90%
85-83-06	746-960	15/0.2 dB	3/97%
85-83-07	746-960	20/0.1 dB	1/99%
85-83-08	746-960	30/0.1 dB	0.1/99.9%

About the Author

Bird Technologies has been the industry's standard in **radio frequency product** reliability for over 70 years. The criticality and definition of "reliability" can range from accuracy and precision to longevity and clarity. The uses can range from commercial applications to military maintenance to electronic military instrumentation. The measures of radio frequency products' quality (and success) can range from data analysis to power measurement to signal strength. Bird Technologies has a single-minded devotion to reliability — no matter the criticality, use, or metrics. Bird = the world's most reliable radio frequency products. With Bird Technologies . . . **You're heard, loud and clear.**

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Part II: The DAS Design Process

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The most common type of the distribution network is a system of coax cables and indoor antennas called a Distributed Antenna System or DAS.

Most of the reference materials and application notes on in-building coverage solutions have focused on the booster technologies or system design architecture. One often overlooked aspect in the system design is the DAS implementation. This includes connecting all the cables and antennas throughout the building and balancing the signal levels at each DAS node. If ignored, an improperly designed DAS results in degraded performance and unnecessary cost increases. This 2-part series of articles is an effort to outline a simple process of designing a DAS in order to achieve the most efficient RF coverage distribution. Part I talks about the Use of Directional Couplers in DAS and Part II covers the DAS Design Process.

Part II: The DAS Design Process

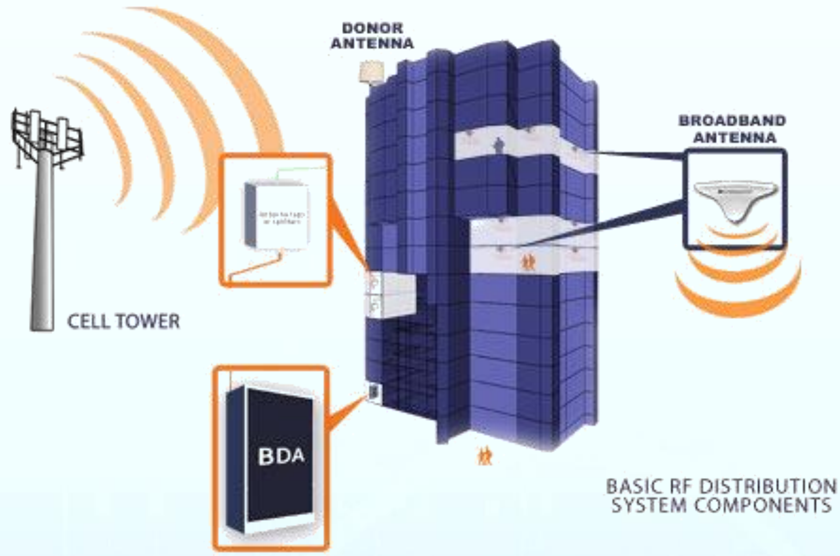
The first step of DAS design is to obtain an accurate and up-to-date blueprint of the building. An architectural drawing is best, but even a fire exit map will suffice, as long as it's drawn to scale. Be careful when using the scale on any drawing to calculate the real dimensions; the piece of paper sitting on your desk may not be the same size of the paper when the drawing was originally made. If it has been shrunk to fit your 8.5x11" printer paper, the "1in = 10ft" scale printed on the drawing is no longer valid. When in doubt, it is always a good idea to double check. Known building dimensions or square footage are also good references. Another simple rule of thumb is to check the opening of a regular single door, which has to have a 36-inch clearance as specified by ADA.

Therefore, when everything else fails, you can always calculate the scale by measuring width of a door on the drawing.

The second step is to make sure you know all the relevant physical information related to the building and the DAS installation. What kind of material was used for exterior construction? Could some RF signals be present on upper floors and near exterior boundaries that will reduce the need for the in-building coverage? What kind of material was used for interior construction, drywall or concrete? Is the building designed for a special application that may result in RF blockage? Many hospitals and power generating plants fall into this category. Are there any restrictions on the cable runs and antennas installation? Some buildings won't allow any visible hardware for aesthetic reasons. Where can the cables go between floors? Where will the head-end booster be located? Answers to these questions will have a great impact on the coverage area for each DAS node, hence dictating where and how the DAS should be installed.

A quick word on another type of DAS: radiating cable. It is essentially a coax cable with lots of tiny slits cut along the length of the cable. Each slit functions as a tiny antenna with RF energy leaking out of it, hence the nickname "leaky cable". The signal levels coming out of the radiating cable are pretty low, so the coverage area is typically no more than 20 or 30 ft on either side of the cable. Therefore, it's better suited for areas that are long and narrow such as tunnels or long hallways. Because of the fact that signals are coming out of the cables throughout, the insertion loss of the cable is typically higher than comparable coax and it's something to keep in mind during the DAS design. For the rest of this article, I will focus on the coax and antenna type of DAS, but the layout of a radiating cable DAS can use the same design guidelines.

With a scaled building blueprint in hand and a good understanding of the particular limitations of the project, the designer can now sit down and map out all the DAS nodes, i.e. locations of the antennas. Typically, an omni-directional indoor antenna with 0 dBd of gain can adequately cover an area with a 100~150 ft radius at 800 MHz, a 200~250 ft radius at UHF, and a 300~400 ft radius at VHF. These numbers are derived from link budgets based on the free space loss at those frequencies and the typical power level put out by the signal booster. Obviously, the designer has to exercise his or her judgment to account for the unique circumstances of the project. The same antenna, at the same frequency, will have very different coverage on an open office floor with cubicles versus coverage on a dormitory with many small rooms separated by concrete walls.



After the location for each antenna node is picked out, the designer "connects the dots," with the lines representing cables in real life. We can measure the length of the cable on paper, and then use the scale to calculate the cable length. The insertion loss for the cable is calculated based on specifications provided by the manufacturer. So, at this point, we know the location and loss of each cable run. See Figure 6 for a simplified drawing of one floor in a building, with two antenna nodes. It's assumed that this DAS covers multiple levels in the building, so there is a vertical cable run that connects each floor. Therefore, we have two antennas on the floor, one cable split for those 2 antennas, and another cable split for the vertical cable run.

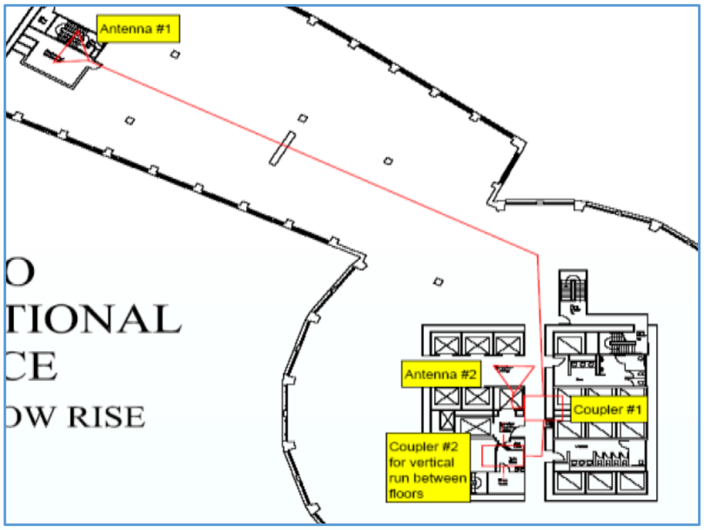


Figure 6.
An Example of One Floor in a Building DAS

In order to make it easier to see, a DAS design is often drawn up with 2 sets of diagrams, one with direct marking on the building blueprint to indicate the location of the antennas and cable splits, and a second set of "abstract" drawings (typically in VisioTM or AutocadTM) showing the cable lengths and coupler models. Figure 7 shows the "abstract" version of the drawing for the same DAS in Figure 6.

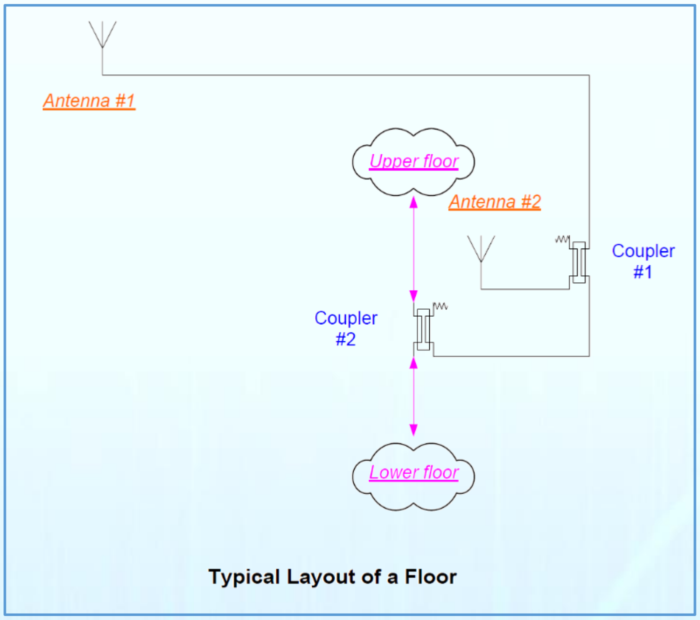


Figure 7.
Abstract DAS Drawing

Here comes the important part of DAS design: how do you connect all the cable segments and antennas to make them into a network? As discussed in Part I of this article, directional couplers are much better alternatives than splitters at this task. They offer various power split ratios to allow the designer flexibility in balancing the power level at each DAS node.

The main goal of using couplers is to offset the difference in cable losses by using the different loss ratios between the two outputs of the coupler. For example, if a cable run is split into two branches, say 15 dB IL in one branch vs. 5 dB IL in the other, we would like to select a coupler that has 10 dB of difference in power split ratios. Put the lower loss port on the higher loss branch, and the higher loss port on the lower loss branch, and Presto: we have two branches with same amount of total losses (including the coupler and the cable). Most manufacturers of directional couplers provide a series of products with different split ratios to allow the designer to match the loss differentials as closely as possible.

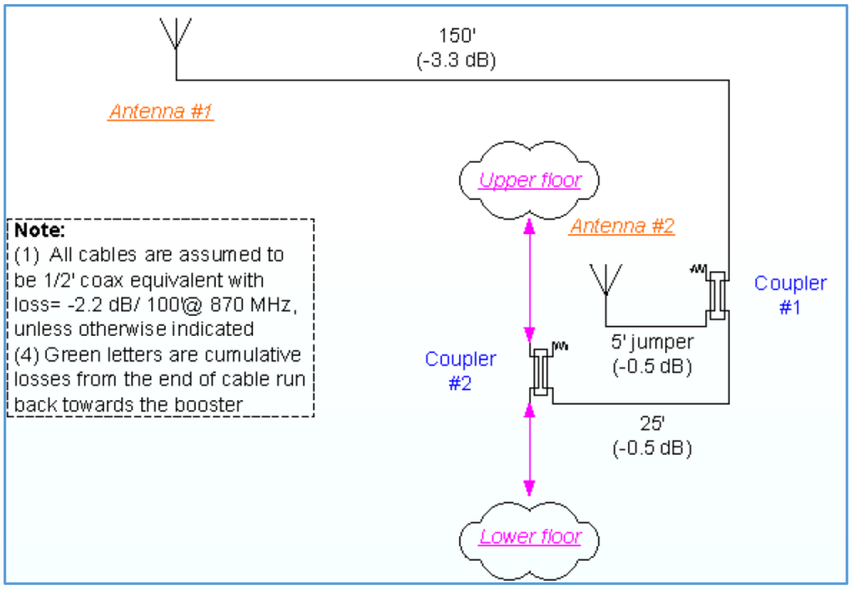


Figure 8.
DAS with Cable Losses

Back to the example we were looking at. In Figure 8, we have a branch with 150 ft of cable with about 3.3 dB of insertion loss, and another branch of 3 ft jumper cable with 0.5 dB of loss. We need to select a coupler that can make up the loss differential in the two cable runs. Browsing through the table of available couplers in a catalog, we select a coupler model number with a 4.8/1.8 dB split ratio as Coupler #1. If we connect the longer cable run to the throughput port with 1.8 dB, and connect the shorter cable run to the coupled port with 4.8 dB, the total losses from the input of the coupler to the antennas are 3.3 + 1.8 = 5.1 dB and 0.5 + 4.8 =

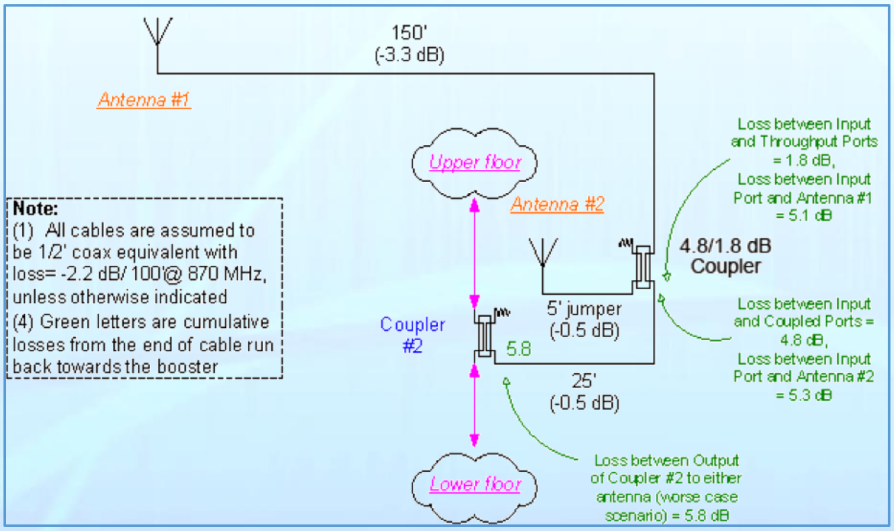


Figure 9.
Calculation of Cumulative Loss in DAS

5.3 dB respectively. If we had used a 3 dB splitter, the total losses would have been 3.3 + 3 = 6.3 dB and 0.5 + 3 = 3.5 dB. Right away, one can see the benefit of using a coupler as it manages to balance the signal levels at the two antennas within 0.2 dB of each other.

Next, we work our way backwards toward the booster. We take the worse number of the two above (5.1 and 5.3 dB, so we use 5.3 dB), and add the 0.5 dB cable loss between the two couplers, we get 5.8 dB, which is the loss from the output of Coupler #2 to either Antenna #1 or Antenna #2. See Figure 9 for the illustration of calculating the cumulative loss.

Now, let's assume there are more floors above this one. The DAS on the upper floor has been balanced using couplers in the same way as illustrated, and the total loss in the DAS on the upper floor has been calculated to be 10 dB. See Figure 10 as we "propagate" the loss in the DAS backwards toward the booster.

Again, we want to select a coupler that will offset the loss differential and balance the signal levels. Browsing through the coupler catalog, we find a coupler with a 6/1.2 dB split ratio. If we connect the 6 dB coupled port to the lower loss DAS on this floor, and the 1.2 dB throughput port to the higher loss DAS on the upper floor, we get 5.8 + 6 = 11.8 dB and 10 + 1.2 = 11.2 dB. Therefore, the total losses from the input of Coupler #2 to the cable runs on this

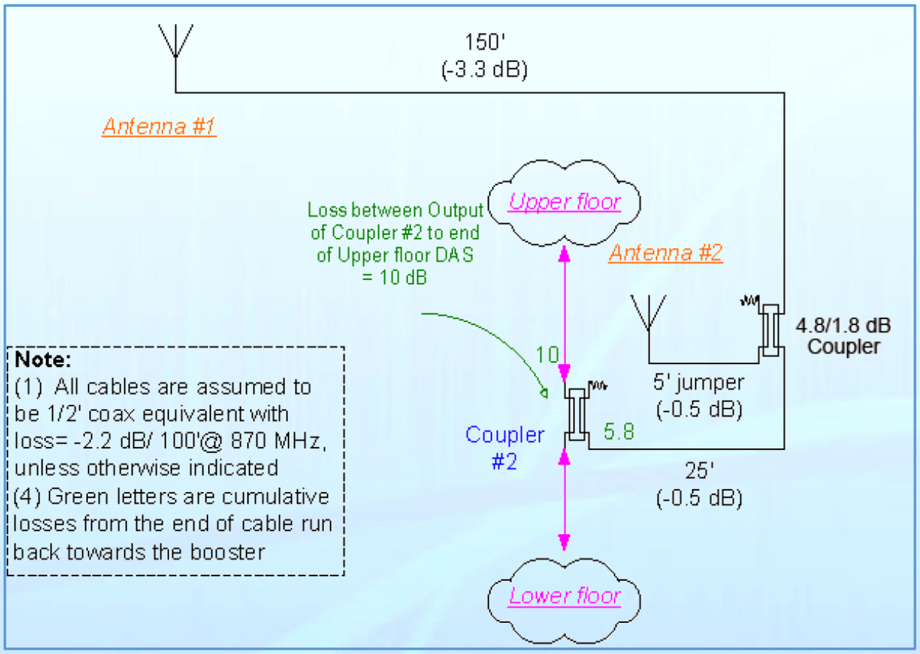


Figure 10.
Calculation of More Cumulative DAS Loss

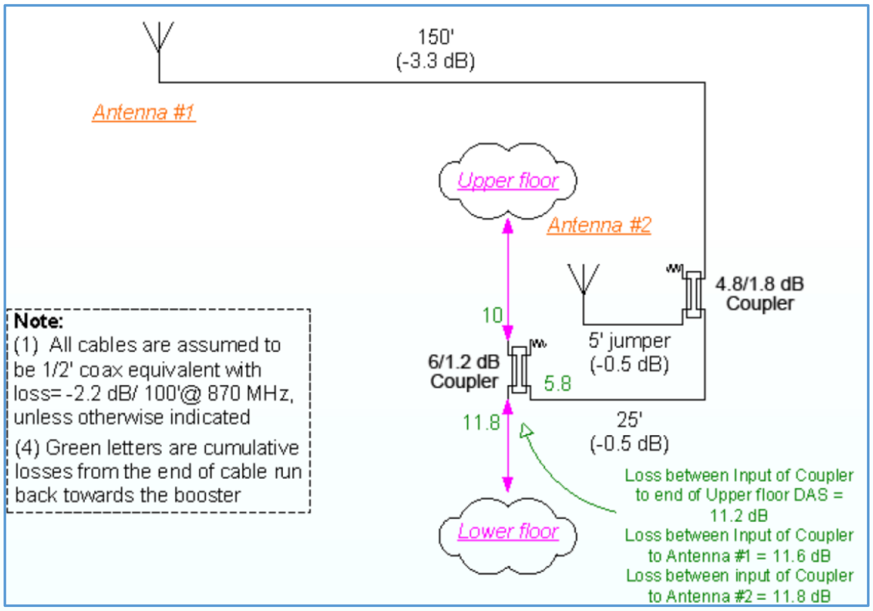


Figure 11.
Completed DAS Design for One Floor

floor and the cable runs on the upper floor are within 0.6 dB of each other. See Figure 11 for a total tally of all the losses.

If there are more floors below it or more cable splits between this one and the booster, the same iteration is to be repeated until we work all the way back to the booster. A typical in-building coverage system can vary from 10,000 sq ft to 1,000,000 sq ft or more, with the number of couplers from a handful to hundreds. However, the rules of calculating the losses and selecting the couplers stay the same, allowing the designer to balance any DAS and achieve the optimal signal levels throughout the network.

As mentioned before, the total DAS loss should be limited to no more than 25~30 dB, in order to maintain a sufficient signal to noise ratio. As we start calculating the loss and selecting couplers from the remote end of the DAS and work backwards toward the booster, we eventually get to a point that the system loss exceeds the limit. We know that we will need to insert an in-line booster at that point. The exact location is of course dependent on the practical constraints of the building, but wherever the in-line booster is, the cumulative loss ends at its output, and starts from zero again on the other side of the in-line booster. Another alternative is to use coax with larger diameters with lower insertion loss. But that option carries its own disadvantages such as high material and labor costs, as well as the physical limitations on bending radius and weight support issues.

In summary, DAS design is a combination of node placement and simple mathematics. Couplers and coax cables do not have the glamour or complexity of the signal booster. However, a little attention to these often overlooked components in the DAS goes a long way to ensure that the performance of the system lives up to the design specification and, more importantly, to the expectation of the customer.

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