WHITE PAPER

HIGH-DENSITY WIRELESS NETWORKS FOR PUBLIC VENUES: CHALLENGES AND BEST PRACTICES

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01. INTRODUCTION

As mobile phones become more affordable, subscriber usage patterns continue to evolve. The primary focus of the second generation (2G) of mobile telephony was on making voice calls on the move; third generation (3G) focus was on accessing emails and sending short text messages when away from a desk. The fourth generation (4G) focuses on accessing the Internet when on the move as if from a desk. While voice users may make a call either on the go or in a restaurant or even at home, heavy internet users are likely to engage in web browsing or data downloading while otherwise idle: commuting to or from work using public transportation, sitting in an airport terminal, taking a break in a food court at a shopping mall, or at halftime during a sporting event in a stadium or arena. Wherever they are, people often seem busy with their smart phones, watching videos or checking status updates.

02. PROBLEM

Wireless carriers are aware that user experience is shaped by the ability to access the network in public venues, and are investing in public venue networks to address coverage and capacity. Most funding is allocated to venues with the highest density of subscribers such as:

- Airports
- Stadiums and arenas
- Underground public transportation (subways)
- Shopping malls.

While each of the above four types has its own design and implementation requirements, they share many common factors. As all four are public venues, the venue network has to provide signals for multiple wireless service providers (WSP) that operate in the area. In many cases the venue manager may also require that public safety ("first responders") and building operations trunked radio signals are carried on the network. IEEE 802.11 networks, commonly known as Wi-Fi, have become so popular that venue managers insist on including them as well. These participants in venue networks are commonly referred to as "network tenants".

03. SOLUTION

In order to provide service to network tenants, a neutral host network capable of supporting a wide range of wireless technologies and spectrum bands needs to be built at the venue. The network also needs to be capable of delivering high-power signals to serving antennas at venues where the distance between subscribers and antennas is large, such as football stadiums. The best choice for such networks is a Distributed Antenna System (DAS) where network infrastructure (transmission cables, power amplifiers and antennas) is shared amongst network tenants. The tenants' base transceiver station (BTS) sectors are collocated within the venue at a location commonly called the "base station hotel". At the base station hotel, RF signals are delivered from the BTS sectors to the DAS headend. The headend combines the RF signals and transports them via an intermediate DAS network to remotely located antennas scattered throughout the venue. There are three types of DAS which differ by the type of intermediate network that connects the headend to the remote antennas: passive; active; and hybrid.

3.1 PASSIVE DAS

A passive DAS consists of a headend, an intermediate passive network, and remote antennas. At the headend, signals from multiple base stations are received and combined into a single signal. This composite signal is then split via power dividers into several parallel composite signals that are sent to remote antennas via a passive network. The passive network consists of coaxial cables, splitters and power dividers. Figure 1 illustrates the passive DAS.

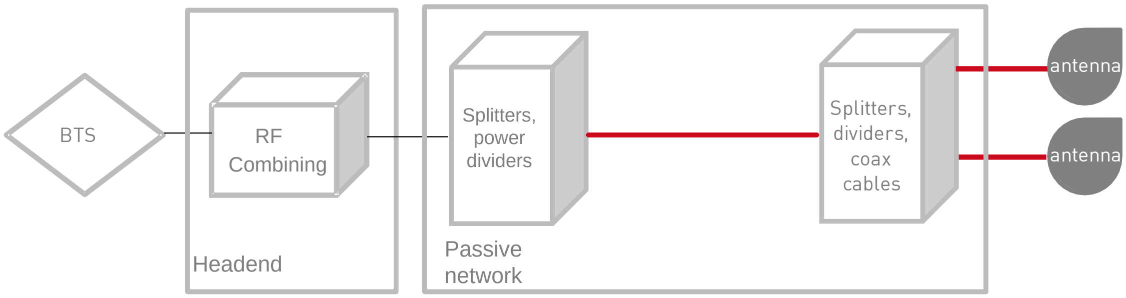

Figure 1: Passive DAS diagram

Base stations used in this configuration are usually macro base stations with transmit power of 20 W (43 dBm). High transmit power is needed to overcome passive losses between the BTS and the remote antennas since there are no intermediate RF amplifiers in the network. Coaxial cables used in the passive network are usually ½" or ¾" in diameter; the latter have lower attenuation per meter but are more expensive and more difficult to install because they are larger and less flexible.

While a passive DAS is less expensive to deploy and maintain than an active or hybrid DAS, its major drawback is the limited distance between BTS and antennas, dictated by passive loss limitations. This is explained in more detail in section 5.3.

3.2 ACTIVE DAS

An active DAS consists of a headend, an intermediate active network, and remote antennas. As with passive DAS, the headend receives signals from several BTS and combines them into a single RF signal. The active network receives the composite RF signal, converts it to optical, splits the optical signal into several parallel optical signals, and sends them via fiber cables further down the network. When the optical signal arrives in the general vicinity of the target coverage area, it is converted to a digital signal and sent via cable TV (CATV) cables to digital/RF power amplifiers, also known as Remote Units (RU). At the RU, the digital signal is converted to RF and amplified. Each remote antenna is located right next to its RU, and is connected to it via a short RF jumper cable (0.5-1m). Figure 2 illustrates the active DAS.

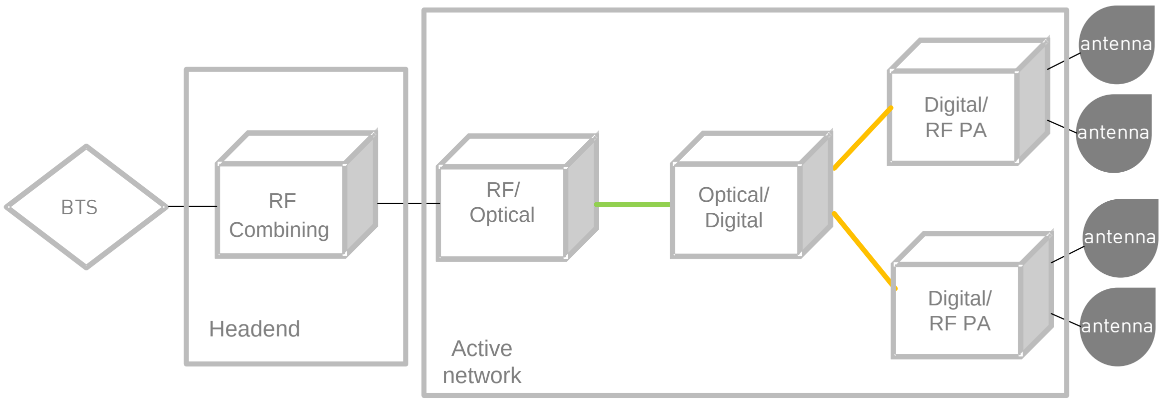

Figure 2: Active DAS diagram

The maximum distance between the RF/optical and optical/digital converters is determined by the optical link budget. The link budget depends on the type of fiber cable (multi-mode vs. single-mode) and the type of optical connectors used, but is in general on the order of a few kilometers. The maximum distance between optical/digital converter and RU depends on the type of CATV cable used since some CATV cable types have less attenuation per meter than others; typical CATV choices are RG-6, RG-11 and RG-59. The system gain between the optical/digital converter and the RU can, to a large degree, cancel out the CATV loss between the two.

Since the remote antennas are right next to the power amplifiers, Equivalent Isotropically Radiated Power (EIRP) from the antennas is uniform, which makes active DAS design and planning easier. Finally, since the power amplifier re-amplifies the RF signal, the BTS signal need not be as powerful as is necessary in a passive DAS. This is important for LTE networks and is explained further in section 5 below, "Common Best Practices".

An active DAS has two major drawbacks. The first is the cost to deploy and maintain the network. The cost to deploy the first RU in a DAS is high, while adding subsequent RUs makes the DAS progressively less expensive. The consequence is that it is rarely cost-effective to deploy active DAS in small venues. The second drawback is the power requirement for RUs, as providing AC power to remote locations adds to the total cost of build-out. In some cases, instead of AC power, RUs can be supplied with DC power over copper, provided composite fiber/copper cable is deployed. The maximum distance over which DC power can be sent to an RU depends on the copper wire gauge and the RU DC power requirements. Typical copper wire gauge values are 12, 14, 16 and 18 AWG [1], while typical power requirements range from 12 VDC [2] to 75 VDC [3].

3.3 HYBRID DAS

A hybrid DAS consists of a headend, an intermediate hybrid network, and remote antennas. As with the DAS networks described above, the headend receives signals from several BTS and combines them into a single RF signal. An active network receives this signal and converts it to optical, then splits the optical signal into several parallel optical signals and sends them via fiber-optic cables further down the network to Remote Units. At the RUs, the digital signal is converted to RF, amplified, and split into a small number of parallel RF signals using power dividers. The RF signals are sent via coaxial cables to remote antennas. In some venues, such as tunnels, radiating cables may be used instead of coaxial cables and remote antennas. Figure 3 illustrates the hybrid DAS.

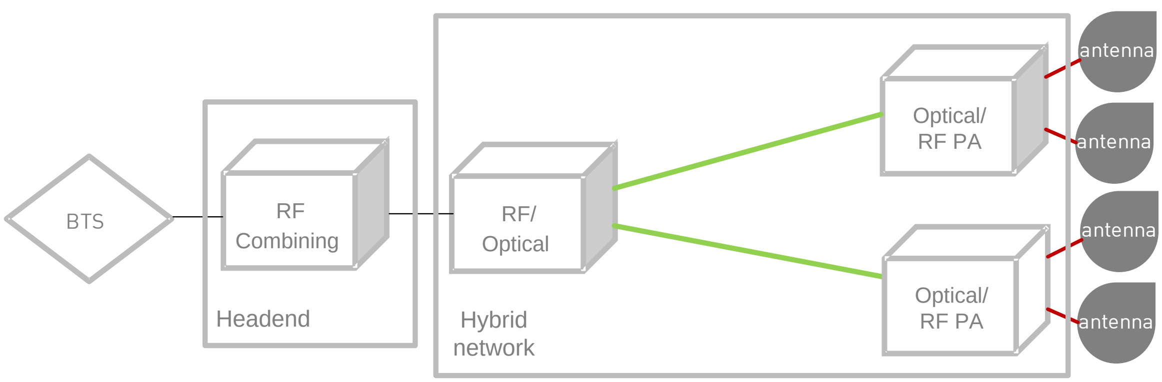

Figure 3: Hybrid DAS diagram

The presence of passive elements (coaxial cables, radiating cables) between antennas and RUs adds attenuation to the RU output signal, making EIRP at the antennas unequal. However, the elimination of optical/digital conversion makes hybrid DAS simpler, with fewer active network elements. It also separates the RU from the antenna which allows the RUs to be mounted in telecom closets, further away from antennas. Typical RU-to-antenna distances range from 10 to 50 meters depending on the RF propagation environment.

04. COMMON DESIGN REQUIREMENTS

Although each public venue has its own particular design and implementation requirements, they have many in common, as expanded upon in the following paragraphs.

4.1 MULTI-CARRIER (NEUTRAL HOST)

The three types of networks most often included in public venue networks are:

- Commercial mobile networks
- Private mobile networks
- Wi-Fi networks

To make the network cheaper, and easier to deploy and maintain, these networks share hardware wherever possible. The shared network is commonly known as a "neutral host" network. Commercial and private mobile networks usually have more than one tenant in the neutral host network.

Commercial mobile networks are operated by WSPs, and WSPs that operate in the same frequency band often share power amplifiers in RUs. Since output power is shared equally among all active RF channels in the band, adding more channels decreases the output power per channel, thus decreasing coverage for all WSPs in the band. To prevent this it is important to include Point of Interface (POI) equipment between the WSP source and the neutral host network, as the POI limits the total amount of power allocated to each WSP. This effectively ensures that a WSP that adds active channels is the only WSP affected by that change.

First responders and venue operations and maintenance operate as private networks. This sort of network uses two-way radio technology and its design coverage scope is typically more extensive as it must cover areas not accessible to the general public. Examples of such areas are delivery docks, electrical and equipment rooms, and areas that need to be accessed during periodic maintenance of the facility.

With the rise of consumer data usage, Wi-Fi networks have become very popular as an inexpensive alternative to cellular data coverage. This technology is now commonly included in in-building networks, and is often used to offload cellular data traffic. Wi-Fi is a common name for IEEE 802.11 technologies that were developed to provide Wireless Local Area Network service. Wi-Fi is mostly deployed and operated by a venue to improve customer experience and to advertise. Although Wi Fi is technically a tenant in the public venue network, due to transmission constraints it shares only remote antennas with the other tenants.

4.2 MULTI-BAND

Neutral host networks transmit both licensed and unlicensed bands. The actual number and type, Frequency-Division Duplex (FDD) or Time-Division Duplex (TDD), of licensed and unlicensed bands vary by region, as summarized in Table 1.

NORTH AMERICA	EUROPE	ASIA
VHF FDD (150 MHz)	VHF FDD (150 MHz)	VHF FDD (150 MHz)
UHF FDD (450 MHz)	UHF FDD (450 MHz)	UHF FDD (450 MHz)
Public safety FDD (800 MHz)	Cellular FDD (900 MHz)	Public safety FDD (800 MHz)
4G FDD (700 MHz)	PCS FDD (1.8 GHz)	Cellular FDD (850 MHz)
Cellular FDD (850 MHz)	AWS FDD (1.9/2.1 GHz)	UMTS FDD (1.7/1.8 GHz)
AWS FDD (1.7/2.1 GHz)	4G TDD (2.6 GHz)	PCS FDD (1.9 GHz
PCS FDD (1.9 GHz)	2.4 GHz TDD (Wi-Fi)	UMTS FDD (1.9/2.1 GHz)
2.4 GHz TDD (Wi-Fi)	5.7 GHz TDD (Wi-Fi)	4G TDD (2.3 GHz)
5.7 GHz TDD (Wi-Fi)		4G FDD (2.5 GHz)
		2.4 GHz TDD (Wi-Fi)
		5.7 GHz TDD (Wi-Fi)

Table 1: Typical spectrum bands found in public venue networks

4.2.1 LICENSED BANDS

Current worldwide licensed bands range from 700 MHz to 2.6 GHz. While different regions of the world may use the same name for a spectrum band, frequency of operation may not be the same. Even more significant is the fact that some spectra, like 4G, are FDD in North America and TDD in Europe and Asia. It is clear that while the advent of LTE has helped to streamline mobile technology across the world, it has done nothing to streamline frequency of operation or the type of licensed spectrum set aside for mobile networks.

The VHF (150 MHz) and UHF (450 MHz) bands are used mostly for two-way radio communications among venue operations and maintenance personnel, and occasionally for public safety. The SMR (800 MHz) band is used exclusively for public safety. Deploying VHF band in public venue neutral host networks is rare, and may increase complexity since it is difficult to find quality DAS equipment that includes the 150 MHz band.

The consequence of having to cover a wide range of frequency bands is that an active DAS may have different values in different frequency bands for gain flatness, maximum intermodulation distortion (IMD), and input third-order intercept point (input IP3) [3].

4.2.2 UNLICENSED BANDS

The most common unlicensed bands are two ISM bands: 2.4 GHz and 5.7 GHz. These bands are shared with other devices such as microwave ovens and point-to-point links, and are used for various Wi-Fi technologies (802.11a, b/g, n, ac). The increasing congestion in these bands has made frequency coordination/frequency planning necessary when planning Wi-Fi networks.

4.3 MULTI-TECHNOLOGY

Public venue networks carry multiple wireless technologies. Since power amplifier linearity requirements differ for different technologies, so does maximum output power [3]. The type and number of technologies vary with region, but most common across the world are GSM, UMTS, LTE and Wi-Fi (802.11). In North America, CDMA2000 and EvDo are common, while PHS and AXGP can be found in Asia. Occasionally, WiMAX (802.16e) can be found throughout the world. The most common trunked radio systems used by first responders and venue operating personnel are TETRA, Tait, Motorola iDEN and Ericsson EDACS. A summary of the technologies most common in North America, Europe, and Asia is given in Table 2.

NORTH AMERICA	EUROPE	ASIA
Trunked radio system	Trunked radio system	Trunked radio system
GSM	GSM	GSM
UMTS (WCDMA)	UMTS (WCDMA)	UMTS (WCDMA)
HSPA	HSPA	HSPA
CDMA2000	LTE	CDMA2000
EvDo	802.11	EvDo
LTE		LTE
802.11		WiMAX
		PHS
		AXGP
		802.11

Table 2: Common technologies implemented in public venues

05. COMMON BEST PRACTICES

While each type of public venue has its own specific best practices, they share some common best practices as expanded upon in the following paragraphs.

5.1 PIM (PASSIVE INTERMODULATION)

Passive Intermodulation (PIM) is a phenomenon that occurs in passive devices (cables, splitters, antennas, etc.) where two or more high-power signals mix. As signal amplitude increases, intermodulation effects become more noticeable. If the spurious signal falls in the uplink frequency range, it may increase noise level, degrade signal quality and reduce uplink capacity. Public venue networks are especially vulnerable because many signals propagate through cables and antennas, and also because some public venues, like stadiums and arenas, use high-power amplifiers.

PIM sources can be external or internal. An external PIM source can be created if an antenna is located near rusty bolts or rusty mounts, such as air conditioning ducts [4]. Internal PIM sources are at the conductor. To locate a PIM source, it is recommended practice to tap antennas and connectors lightly during PIM testing to see if a PIM spike results. Periodic PIM inspections and keeping antennas and equipment clean is essential for good performance of neutral host networks.

A bad connector is one with an improper attachment of connector to coaxial cable or a connector that is corroded. When a bad connector is identified, it needs to be disconnected, taken apart and inspected for physical damage or contamination. When reassembling connectors, care should be taken not to twist them. Small scratches caused by twisting can generate both VSWR and PIM. All tightening of connectors should be done using a torque wrench. Inadequate torque will leave gaps which may cause PIM; excessive torque may damage the center connector.

Coaxial cables cause PIM if damaged or poorly terminated. If coaxial cables are cut at installation, care should be taken to clean debris from the cable because debris inside a connector may create PIM. To properly terminate cables, a connector clamping tool should be used to set the center pin depth correctly. It is recommended to use 7/16 DIN connectors for termination because they are made specifically to counteract PIM and therefore are preferred over N type connectors.

5.2 DOWNLINK DESIGN

Thermal noise in LTE is referenced to the Physical Resource Block (PRB), which has a channel width of 180 kHz. Thermal noise referenced to PRB is equivalent to 121 dBm. If the PIM signal is kept at least 6 dB lower than thermal noise (-127 dBm), then the combined PIM signal and thermal noise is approximately -120 dBm. The difference between thermal noise and thermal noise combined with PIM is 1 dB, which means that the presence of PIM increases the noise level by 1 dB. This noise increase is deemed acceptable, and therefore the goal is to keep PIM at -127 dBm or lower in LTE networks.

In UMTS passive networks the BTS sector transmits at full power, 20 W (43 dBm) per channel, in order to overcome passive network losses. In those networks, the required PIM rating of combiners used at the headend when two 43 dBm carrier signals are applied needs to be 155 dBc [5], or 155 decibels below the input carrier signal. Acceptable UMTS PIM level is then 43 - 155 = -112 dBm.

Since acceptable LTE PIM level (-127 dBm) is lower than acceptable UMTS PIM level (-112 dBm), LTE transmit power per PRB also has to be lower than UMTS transmit power per channel. For LTE networks, combiners with 162 dBc rating at 2x35 dBm input power are used at the headend [5]. These are able to meet LTE PIM requirements as 35 – 162 = -127 dBm. Note that maximum LTE transmit power per PRB (35 dBm) is 8 dB lower than maximum UMTS transmit power per channel (43 dBm). Assuming the same antenna EIRP in both UMTS and LTE passive DAS networks, this means that in LTE networks the maximum passive network loss is reduced by 8 dB. If the passive network loss is reduced by 8 dB, the passive LTE DAS will need more sectors than the passive UMTS DAS to cover the same area.

Unlike in passive DAS, in active and hybrid DAS the BTS sector signal is re amplified in the DAS network before being sent to the remote antennas. For that reason, the BTS sector signal can be comfortably reduced to lower levels to satisfy LTE PIM requirements at the headend without impacting remote antenna coverage radius or sector count.

5.3 UPLINK DESIGN

For LTE networks, low latency and high data rates are the key to customer satisfaction. To achieve high data rates, SINR has to be high. Figure 4 shows the relationship between uplink (UL) data rate per Physical Resource Block (PRB) and Signal-to-Noise Ratio (SNR).

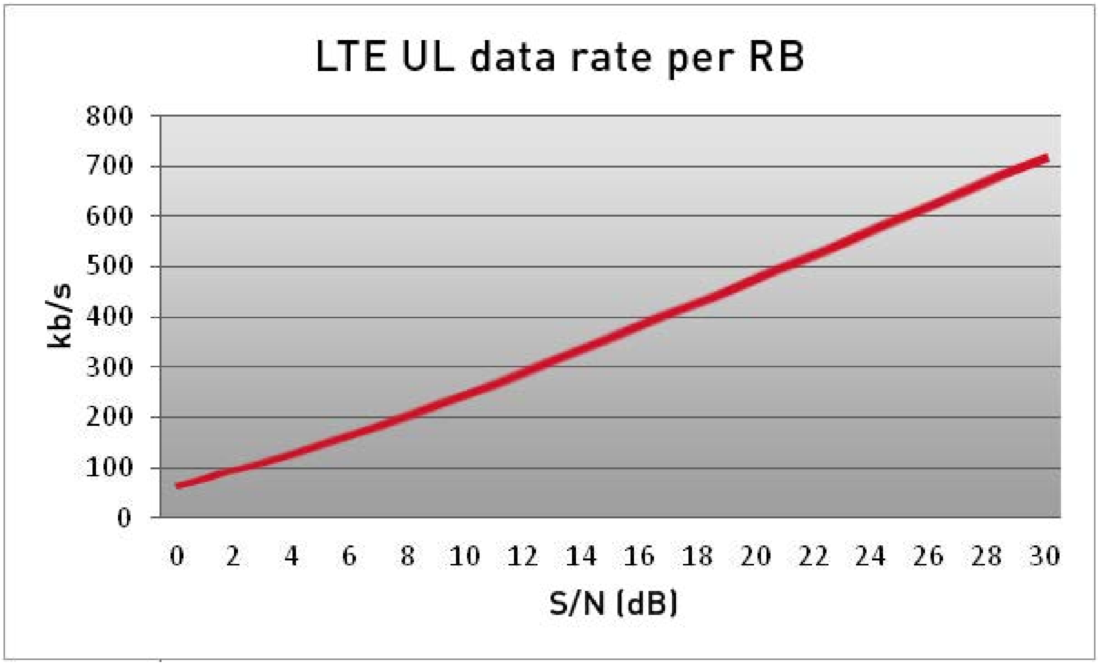

Figure 4: Uplink LTE data rate per Resource Block

As the PRB is the primary building block in LTE, UL data rates are increased by giving a subscriber more PRBs to transmit. Although a large number of aggregated PRBs with low individual data rates may achieve the desired composite uplink data rate, the goal is to minimize the number of PRBs needed by keeping signal-to-interference-plus-noise ratio (SINR) high. In the next two examples, we examine uplink Signal to Noise Ratio (SNR) values for comparable neutral passive and active DAS networks. We assume that the DAS has 16 antennas and is powered by four WSPs, that each WSP has one sector that has output power of 35 dBm per LTE channel, and that the LTE network operates in a channel which is 10 MHz wide (50 Resource Blocks).

The passive DAS architecture is shown in Figure 5. It has one 4x4 hybrid combiner and four 4x1 splitters that have 6.5 dB insertion loss each, so the combined combiner and splitter loss is 13 dB. Passive DAS loss is different for each antenna and, to calculate the link budget, one DAS antenna needs to be selected to calculate the loss. Total coaxial cable length from the BTS to the selected antenna is 87 meters and, with cable loss of 11.5 dB per 100 meters, coaxial cable loss is 10 dB. In the link budget shown in Table 3, the passive DAS loss (combiner + splitter + coaxial cable) for the selected antenna is 23 dB.

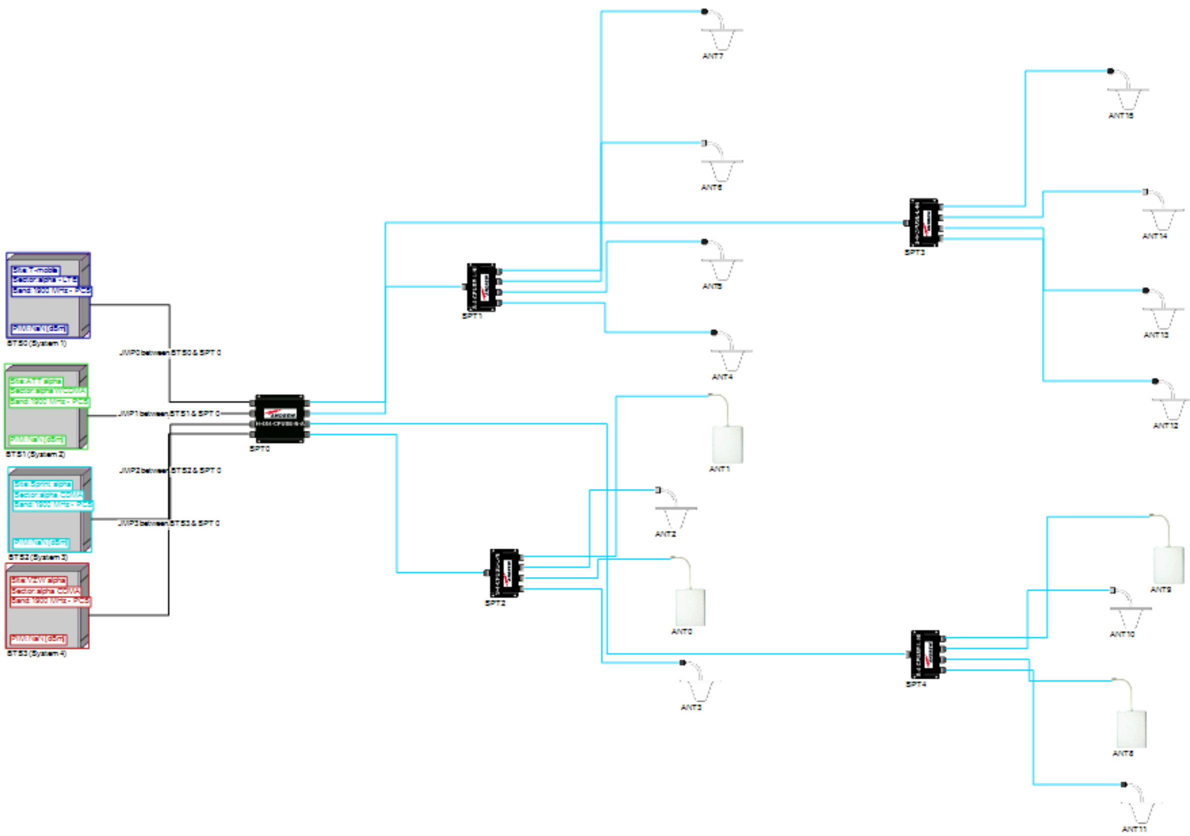

Figure 5: Passive DAS architecture

		VALUE/UNIT	CALCULATION
A	BTS Power	35 dBm	
B	Passive Loss	18.1 dBm	
C	DL Signal at Antenna Input	16.9 dB	A-B
D	DAS Antenna Gain	3.0 dBi	
E	DL EIRP	19.9 dBmi	C+D
F	DL RSRP Threshold	-85 dBm	
G	Antenna to UE prop. loss	104.9 dB	E-F
H	Thermal Noise @ 10 MHz channel	-104 dBm	
I	UE Tx Composite Power	24 dBm	
J	UL Signal at DAs Antenna	-80.9 dBm	I-G
K	S/N at DAS Antenna	23.2 dB	J-H
L	UL Signal at BTS input	-96.0 dBm	J+D-B
M	Noise at BTS input	-104 dBm	H
	S/N at BTS input	8.0 dB	L-M

Table 3: Example of passive DAS link budget calculation

In the uplink, the noise per channel at the remote antenna is at thermal noise level. It does not change from antenna to RF source because the DAS is passive and cannot generate noise by itself. Therefore, the noise level at DAS antenna input and at the BTS sector input are the same. However, the UE signal does change because the passive DAS attenuates the signal as it passes from DAS antenna to BTS sector. The amount of signal attenuation is equal to the difference between the DAS antenna gain (3 dBi) and the passive loss (23 dB), which is 20 dB. This signal attenuation also reduces uplink SNR by 20 dB, as uplink SNR drops from 28.1 dB at the input of the DAS antenna to 8 dB at the BTS sector input. From Figure 4, we see that SNR = 8 dB gives a data rate per RB of 200 kHz.

For the hybrid DAS, we use a high-power Andrew ION™-B active DAS. Four Remote Units are used, each of which has a single output port that connects to a four-way splitter. Each splitter output connects to an antenna using coaxial cable. The hybrid DAS is shown in Figure 6.

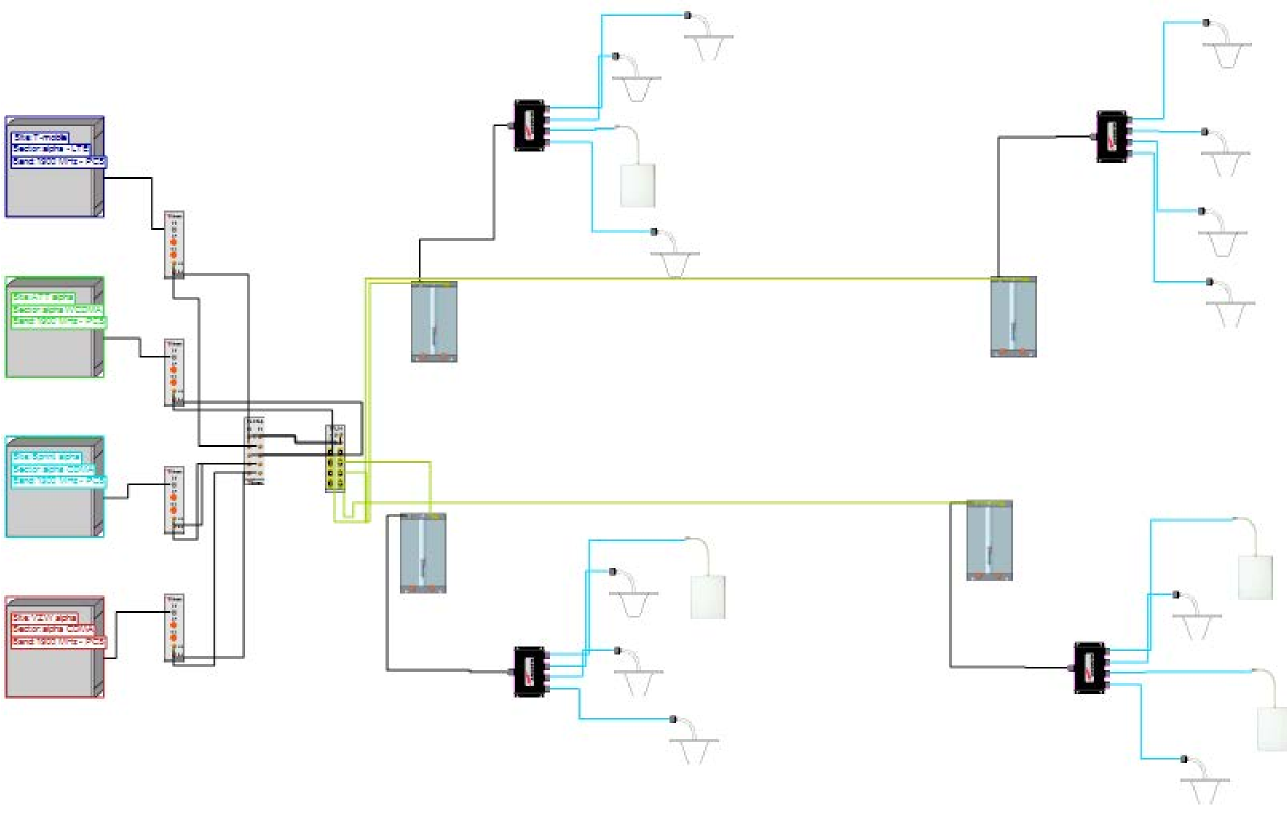

Figure 6: Hybrid DAS architecture

The composite transmit power of the Remote Units is specified for each spectrum band and is shared among all WSPs that transmit in that band. Power per RF channel depends on the number of RF channels in the band. Composite RF power per Remote Unit (30 dBm) is divided equally amongst 6 RF channels, giving a transmit power per channel of 22.8 dBm. The Remote Unit uplink gain is 15 dB, and noise is 7 dB. The uplink filter and combiner losses at the headend are 11 dB. Since coaxial cable runs differ from antenna to antenna, one antenna needs to be chosen to calculate the link budget. In the link budget example shown in Table 4, coaxial cable loss is 3.7 dB which corresponds to a distance of 32 meters.

	DOWNLINK LINK BUDGET	VALUE/UNIT	CALCULATION
A	BTS Power	35 dBm	
B	RU Power	30 dB	
C	DAS Antenna Gain	2.95 dBi	
D	Cable Loss	3.5 dB	
E	Downlink EIRP	29.5 dBmi	B+C-D
F	RSRP Threshold	-85 dBm	
G	Antenna to UE prop. loss	114.5 dB	E-F

Table 4a: Hybrid DAS downlink link budget

	UPLINK LINK BUDGET	VALUE/ UNIT	NOISE LEVEL (dBm)	CALCULATION	SIGNAL LEVEL (dBm)	CALCULATION	S/N (DB)
A	UE Tx composite power	24 dBm	-				
B	UE to antenna propagation loss	114.5 dB					
C	DAS antenna gain	2.95 dBi					
D	Cable loss	3.5 dB					
E	At RU input		-104	-174 + 10log(10 MHz)	-91	A-B+C-D	13.0
F	RU gain	15 dB	-				
G	RU NF	7 dB	-				
H	Number of RUs per Fiber Hub	4	-				
I	Composite NF at Fiber Hub	4	-	G+10log(H)			
J	At Fiber Hub input		-91	E+I	-76.0	E+F	15.0
K	Number of Fiber Hubs	4	-				
L	Jumper cable loss	0.5 dB					
M	TLCN4-W splitter loss	7.1 dB					
N	At TLCN4-W splitter output		-92.6	J-L-M+10log(K)	-83.6	J-L-M	9.0
O	Jumper cable loss	0.5 dB					
P	TLCN4-W splitter loss	7.1 dB					
Q	Splitter output		-100.2	N-O-P	-91.2	N-O-P	9.0
R	Jumper cable loss	0.5 dB					
S	TPOI filter loss	4.0 dB					
T	Jumper cable loss	0.5 dB					
U	BTS imput		-104.0	Q-R-S-T	-96.2	Q-R-S-T	7.8

Table 4b: Hybrid DAS uplink link budget

Unlike a passive DAS, a hybrid DAS generates uplink noise through uplink amplifiers. In this example, four remote amplifiers (remote units) generate a composite NF of 13 dB at a Fiber Hub. This composite NF and the amplifier gain increase the noise per channel from the thermal level (-104 dBm) to -76 dBm. However, splitters, filters and cable jumpers insert a 13 dB loss in the uplink, thereby reducing the noise level to -89 dBm at the base station input. While UL noise increases 15 dB, the UL signal traversing the same path gains only 2 dB, so the SNR drops 13 dB from 20.8 dB at the RU input to 7.8 dB at the base station input.

If we compare hybrid DAS UL SNR with passive DAS UL SNR we may conclude that the two have similar performance, as their UL SNR is almost the same. However, in this passive DAS example, the distance from the antenna to the BTS is 87 meters and extending this distance further would reduce downlink antenna coverage. In hybrid DAS, it is the distance between the antenna and the RU that limits downlink antenna coverage. The RU may be placed up to a few kilometers away from the optical/RF converter, which is usually collocated with the base station at the headend. Therefore, hybrid DAS can reach areas that are further from the base station than can passive DAS, which gives hybrid DAS more deployment flexibility with the same uplink performance. The active DAS UL SNR calculation, omitted for the sake of brevity, is very similar to that for the hybrid DAS, the only major difference being that the active DAS does not use coaxial cables, only jumper cables.

06. CONCLUSION

Although public venues vary in size and RF morphology, neutral host networks that provide coverage at those venues share some common design requirements and best practices. Within the neutral host network, PIM generation is an important concern as poor installation or poor choice of antenna location can generate PIM that otherwise cannot be detected through RF design. LTE networks are most sensitive because they require very low PIM levels to operate properly. In order to satisfy LTE PIM requirements transmit power per LTE PRB is lower than transmit power per UMTS channel, which increases the number of antennas and sectors in a passive LTE DAS compared with a passive UMTS DAS. While passive and active DAS may have comparable uplink data rates, passive DAS antennas need to be closer to the headend to maintain downlink coverage. Passive DAS needs double resources (coaxial cables, splitters) for LTE MIMO. All these factors imply that passive DAS is not a good choice if an LTE network is to be included in a public venue neutral host network.

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