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Connecting the dots: small cells shape up for high-performance indoor radio

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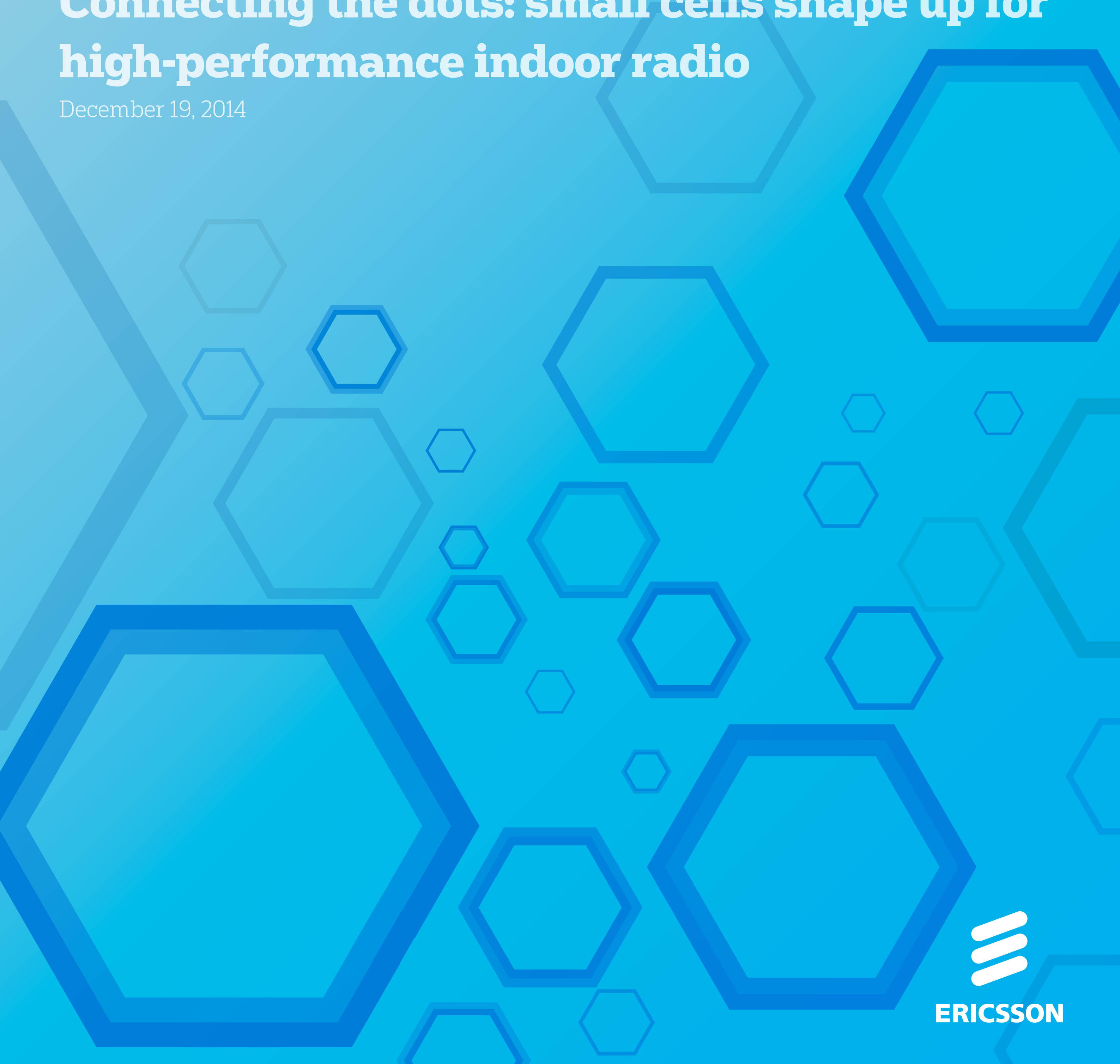

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Connecting the dots: small cells shape up for high-performance indoor radio

In 2012, the global consumption of mobile data traffic in a month amounted to 1.1 exabytes. This figure is set to rise to 20 exabytes by 2019, corresponding to a CAGR of 45 percent[1]. Today, this traffic is split 70/30 with the larger proportion consumed indoors; a level that is not expected to decrease. Adapting networks to support such a rapid rise in traffic demand will require massive deployments of targeted indoor small cell solutions, complemented by denser outdoor deployments.

CHENGUANG LU, MIGUEL BERG, ELMAR TROJER, PER-ERIK ERIKSSON, KIM LARAQUI, OLLE V. TIDBLAD, AND HENRIK ALMEIDA

How do you design a small radio to fit the interiors of large spaces, yet powerful enough to meet future requirements for indoor radio capacity? This was the question we asked ourselves when we began to develop a solution to provide high-capacity radio for indoor environments.

What we wanted was a solution that could provide high-performance connectivity, in the increasingly demanding indoor radio environment. We wanted the installation process to be simple and to reuse existing building infrastructure. We needed to find an efficient way to deliver power and a design that integrates well with outdoor solutions.

The result, the Ericsson Radio Dot System (RDS), is a novel indoor small cell solution with a flexible radio architecture for providing high-capacity indoor radio. This article presents how we overcame the challenges.

Managing mobile data traffic volumes is already a challenge in many markets, and as traffic trends continue to rise, the need to efficiently manage indoor traffic becomes more significant. Some of the factors contributing to the challenge of data traffic are:

- **new energy-efficient building standards – resulting in higher attenuation in outer walls and windows;**
- **global urbanization development – today, 54 percent of the world's population live and work in dense city environments, a figure that is forecast to rise to 66 percent by 2050[2]; and**
- **the gradual consumption shift from laptops to smartphones[3] boosted by network enablers, application adaptations, and device evolution.**

Meeting the requirement for more indoor capacity calls for a combination of macro network extension and densification, together with specific targeted indoor small cell solutions.

To handle peak rates, high capacity small cells require the same level of backhauling capabilities and baseband processing as larger cells. However, when compared with larger cells, the cost of backhauling and other resources (such as baseband processing capability) for small cells typically needs to be balanced against the fewer numbers of users served. So, the ability to simplify backhauling and provide a means to support shared baseband and higher layer processing across many small cells becomes critical.

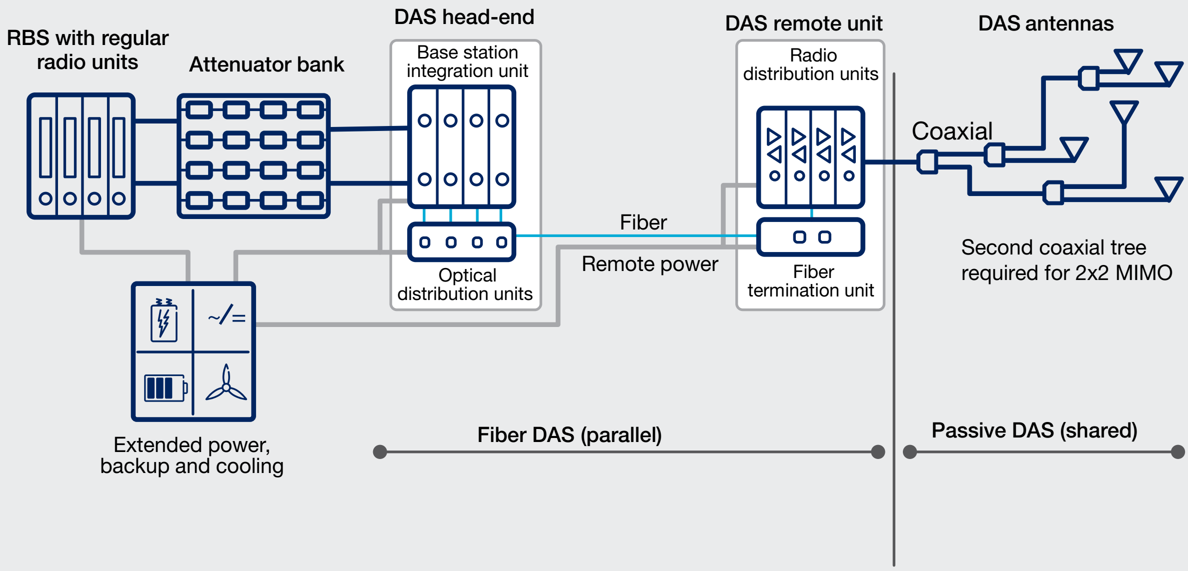
Femtocell-like solutions, with baseband and cell definition at the antenna point, were thought to be candidates for indoor capacity needs. Unfortunately, these types of nodes only work in practice for small deployments, because radio coordination and cell planning quickly become unmanageable as the number of cells increases. For medium to large buildings, venues and arenas, macro cell features like coordination, seamless mobility and interference management are needed. Supporting these features points us in the direction of concepts like main-remote and fronthauling, and solutions that use common baseband processing for remotely deployed small cell radio heads.

For small cell indoor scenarios, the preferred transmission medium is largely dictated by economies of scale. For example, the ability to use the same type of cabling and building practices

BOX A Terms and abbreviations

ACLR	adjacent channel leakage ratio	PoE	Power over Ethernet
CAGR	compound annual growth rate	RDS	Radio Dot System
CPRI	Common Public Radio Interface	RF	radio frequency
DAS	distributed antenna system	RRU	remote radio unit
DU	digital unit	RU	radio unit
FDD	frequency division duplexing	SCC	secondary component carrier
IF	intermediate frequency	SDMA	spatial division multiple access
IRU	indoor radio unit	SINR	signal-to-interference-plus-noise ratio
MIMO	multiple-input, multiple-output	TCO	total cost of ownership
O&M	operations and management	TDD	time division duplexing
PCC	primary component carrier	UE	user equipment

FIGURE 1 Reference architecture – distributed antenna system



as those that the IT industry uses for Ethernet services would be advantageous for any solution. Twisted-pair copper LAN cables are particularly attractive, as they tend to be deployed abundantly within enterprises and are widely supported by the IT community. Installing these cables is a relatively simple process, as it does not require specially trained staff or expensive tools. And in addition, the whole IT ecosystem for LAN cables can be leveraged – from installation and support staff, to established installation and maintenance practices, as well as technologies for fault localization and diagnosis.

Making use of LAN cables is one important characteristic of the Ericsson RDS, which also benefits from being able to reuse existing tools developed for fault localization, diagnosis and copper cabling. Using copper cables to connect radio equipment has the additional benefit of remote powering – power is fed over the same medium as the communications signals. This reduces the complexity and cost of installation, as there is no longer any need to arrange for local power, which can be a costly process. Remote powering from a central location makes it much easier to provide backup power at the central location, thereby increasing reliability.

The major challenge of a traditional fronthauling solution over LAN cables is meeting the requirements for latency and its variation, as well as for high capacity and reach. With the current limitations of the CPRI protocol[4], it would not be possible to apply a main-remote (digital unit (DU)-radio unit (RU) split) concept over longer distances using copper cables. As discussed later in this article, there are additional reasons – like power efficiency and small cell complexity – for not pursuing CPRI as it is currently specified.

Our mindset during the conceptualization of the RDS was one of rethinking the ecosystem around how to secure radio access capacity for indoor environments, taking costs into consideration, as well as simplicity of installation and operations, power feeding and the existing indoor infrastructure. We wanted to create a solution that would fully unleash the capabilities of existing and future radio-access solutions and all of their features[5].

Our starting point was to take a view of the indoor small cell as an extension to and an enhancement of the macro cellular network. We revisited the RU architecture in such a way that deployed radio heads would be connected to the rest of the network via LAN cables, while still fulfilling the goal to have a fully coordinated radio-access network.

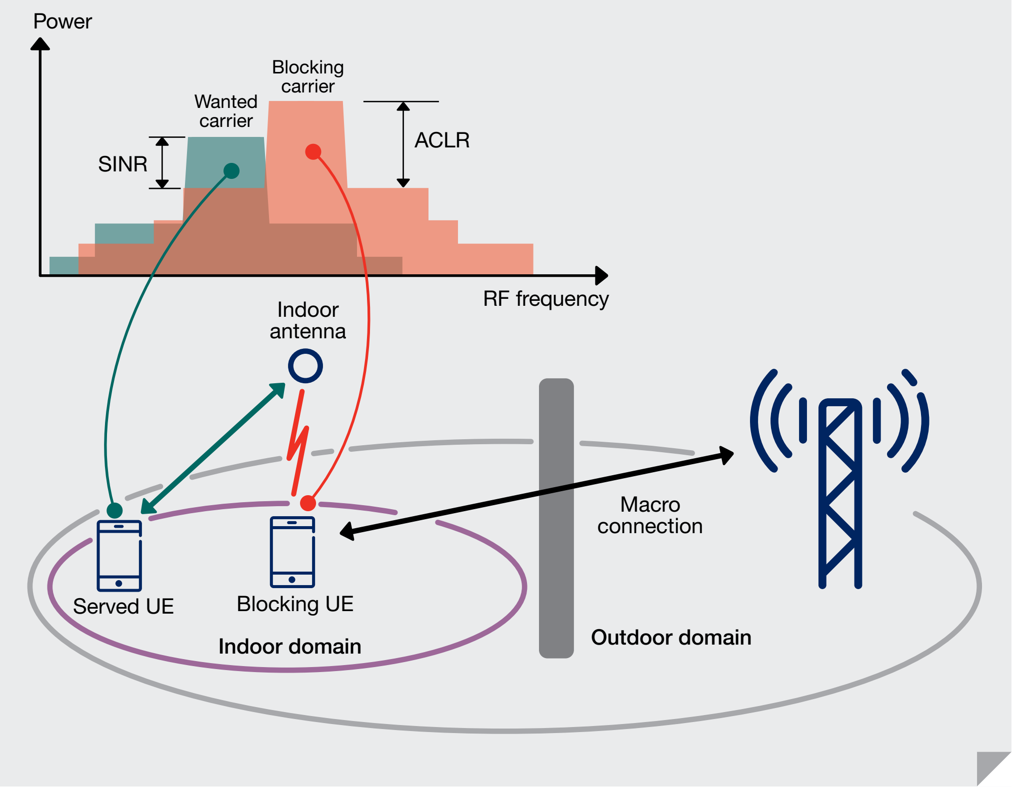
Today's in-building system

Supporting users in indoor environments has been a challenge since the start of mobile networking. For the last two decades, this challenge has been overcome by using a method referred to as distributed antenna system (DAS).

The many flavors of DAS solutions are all based on the principle of redistributing macro RBS radio signals across an indoor antenna grid in the downlink, and a corresponding collection of the user traffic in the uplink. As illustrated in **Figure 1**, this can be achieved by using a passive coaxial RF distribution network, or by using an active fiber-coaxial hybrid network.

Distributed antenna solutions have worked well for many years and are still considered for multi-operator and neutral host applications. However, the technology becomes limited as requirements for higher capacity and capabilities increase and more advanced services evolve. The DAS model originates from large-cell radio architecture, and it is good for voice and basic data coverage, but the radio bandwidth per user it provides is too low to be a viable solution as capacity needs rise.

FIGURE 2 The uplink near-far problem – a UE connected to an outdoor macro degrades SINR for the UE served by the indoor system



The capacity challenge is of particular interest for mobile enterprise scenarios, as application usage shifts from legacy laptop systems to smartphone-based consumption, which rapidly increases indoor-radio capacity requirements. In many markets, the shift to smartphone consumption has already occurred for basic applications such as e-mail, and is increasing rapidly as major enterprise and consumer applications are adapted for smartphone usage.

Indoor radio challenges

Usage in indoor cellular environments is shifting from traditional voice coverage to smartphone app coverage and high performance mobile broadband. For this transformation to succeed and result in an immersive experience of nearly-instantly available data, much higher capacity per unit area is needed compared with existing solutions. However, with the high outdoor-to-indoor penetration loss of modern buildings, an improved indoor system is necessary. For other scenarios, advanced outdoor macro cells with MIMO, carrier aggregation and beamforming are suitable.

Pushing down the uplink receiver noise level to a few decibels above the thermal noise is a successful approach to extend the reach of a macro radio, but is useless for indoor radios. Instead, dense antenna grids are necessary to combat the uplink near-far effect – spectral leakage from user equipment (UE) near an indoor antenna, but connected to an outdoor macro cell and transmitting on an adjacent carrier, can substantially degrade uplink signal-to-interference-plus-noise ratio (SINR) of the indoor node, possibly to the point where service outage occurs.

This near-far effect is illustrated in Figure 2 and cannot be mitigated by filtering in the base station, as noise from the blocking UE is inside the carrier bandwidth of the served UE. For a 20MHz-wide LTE uplink carrier, the maximum allowed spectral leakage in the adjacent channel (ACLR) is 30dB below the carrier power[6]. For example, a UE transmitting at 1.7GHz to an outdoor macro cell using maximum transmit power, and assuming a distance of 1m between the UE and the indoor antenna, yields an SINR degradation corresponding to an effective uplink noise figure as high as 58dB.

The near-far effect does not affect peak rates since it is not present all the time. Once it is present, however, it puts an upper limit on the coverage radius per antenna due to the risk of service outage. In the given example, service outage could occur already with a coverage radius of 20m, depending on UE capabilities and indoor propagation conditions. For such dense deployments, fairly high levels of uplink noise can be tolerated without performance degradation. Instead, focus should be placed on a design that enables coordination as well as fast and flexible deployment.

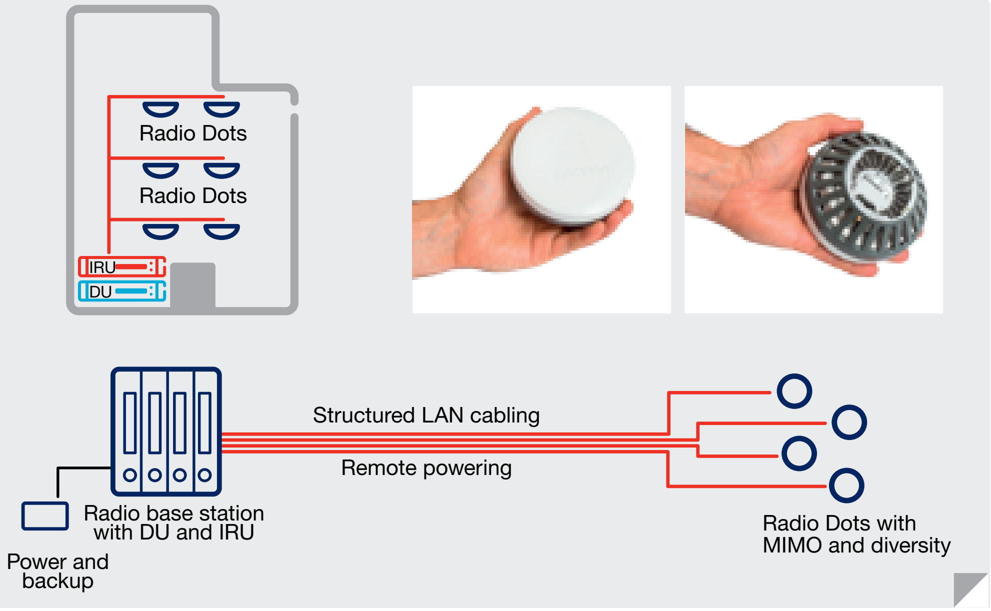
One particularly important requirement for the large building segment is the need for tight coordination, to handle the dynamic traffic situations that arise in complex radio environments like modern atrium buildings with open offices.

Attempts to apply the femtocell model in such environments, which lack natural cell borders, have proven to be challenging. Instead of increasing capacity, reducing the cell size often leads to reduced performance and increased risk of dropped calls due to inter-cell interference and frequent handovers. At low loads, peak data rates may become limited by control channel pollution, as each cell needs a dedicated and robust control channel. Thus, deployment of femtocells creates a huge challenge in terms of performance and TCO. To maintain user satisfaction, supporting interference management and seamless mobility are crucial – between the cells inside the building and between outdoor and indoor cells. This level of coordination is simply not present in femtocell solutions.

The ability to add new features through software upgrades, avoiding site visits as far as possible, is a key success factor for indoor radio deployments. To ensure a consistent user experience with full performance and service functionality throughout the network, having the same set of radio features in the indoor segment as in the outdoor macro RBS is desirable. This also enables coordination between the indoor and the outdoor environment and simplifies network operations and maintenance (O&M). Coherent QoS, high-quality voice, and good mobility support, including for instance soft handover for WCDMA, are examples of features that will be important for user satisfaction both indoors and outdoors.

As well as meeting requirements for increased performance, enabling large-scale rollouts requires a substantial reduction in complexity of installation. Reusing LAN cables is one key way of achieving this. In addition, indoor radio containing active equipment must support remote powering, like PoE or PoE+, as the need for local powering in the event of a power outage could substantially increase deployment costs and decrease availability.

FIGURE 3 **Radio Dot System – indoor made simple**



Key design considerations

Given the challenges, new generations of indoor radio systems need to be designed smartly, adopting best practices from existing indoor systems – DAS, Wi-Fi, and Pico – and embracing new features.

Feature parity

To achieve the desired performance gain from cell size reduction, combined cell technology with spatial division multiple access (SDMA), coordinated scheduling and other advanced coordination features are needed. Such features are already available in macro environments, and sharing the same software base for indoor and outdoor radios greatly simplifies the implementation of feature parity.

A convenient approach is to use the same family of DU, which is also referred to as the baseband unit. DAS is based on such a design using the same hardware and software to drive all antennas in both the indoor and the outdoor macro network.

Fronthauling with LAN cables

To facilitate deployment of smaller cells with full coordination and scalability for high capacity, a fronthaul architecture with a star topology is desired. This approach enables each radio head to be fronthauled individually, resulting in an indoor radio solution that is capable of supporting high capacity while retaining maximum flexibility. The use of LAN cables means that several indoor systems can be deployed within the same budget and time limitations as is required for a typical DAS – as the traditional method of fronthauling requires a fiber deployment. The design challenge in this scenario is how to fronthaul effectively through LAN cables.

Form factors

One concept related to the Internet of Things is that of miniaturized design or integration of communication into everything in a natural way. For our indoor system design, an ultra-compact form factor for the radio heads was one of the most important design considerations. To achieve compactness, low power design is essential so that the heat can be dissipated without affecting equipment reliability. The target is a compact radio head that is smaller than current DAS antennas, with a minimalist design suiting any indoor environment.

Support for high bandwidth

To meet ever-increasing capacity demands, high bandwidth is essential for high-performance radio systems, which can be achieved through carrier aggregation in wide FDD and TDD bands. Additional benefits will come from the adoption of 4x4 MIMO, which should occur in the near future, doubling the total bandwidth capacity.

A novel indoor radio solution

As a new generation of indoor radio systems, the RDS has been developed with these key design considerations in mind, based on technology already developed for RBSs, but with a focus on reducing architecture complexity, enhancing system scalability and improving radio system performance. The design utilizes LAN cabling infrastructure to connect the active antenna elements – which are called Radio Dots.

The system specifically targets use cases that are demanding in terms of performance and dynamic capacity allocation – scenarios that typically require multi-antenna grids, such as medium- to large-size office buildings. For areas with less demanding capacity requirements, such as parking garages or outdoor areas in a campus environment, the RDS can often be complemented with remote radio unit (RRU)-based micro DAS.

As **Figure 3** shows, the RDS has three key components: the Radio Dot, the indoor radio unit (IRU) and the DU.

Digital unit

The DU provides pooled baseband processing for the system. To manage the connected radios, the DU uses the CPRI standard for the DU-IRU interface to transfer synchronization, radio signals and O&M signals. When collocated with the IRU, an electrical CPRI interface is used, and for remote connection with the IRU, a CPRI fiber interface is used.

Indoor radio unit

A newly designed RU that incorporates existing macro software features, extending them with new indoor features. The IRU connects to each Radio Dot using a proprietary IRU-Radio Dot interface over a LAN cable (detailed further on).

Radio Dot

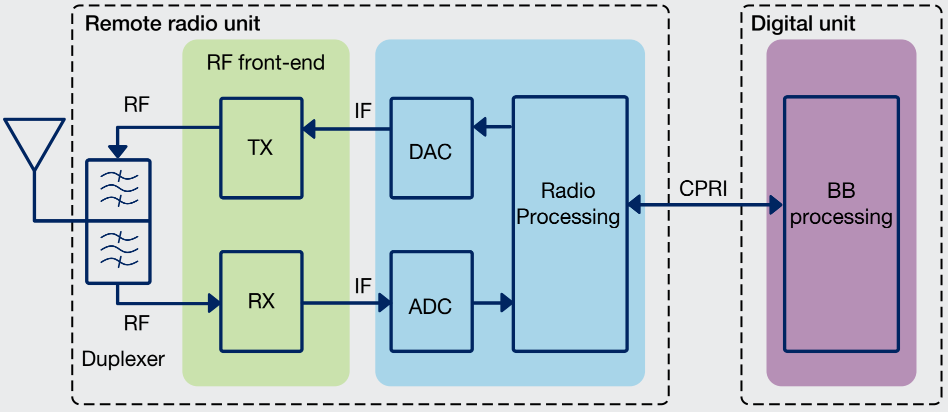
The Radio Dot has two integrated antennas in a 10cm form factor and weighs under 300g. Each Radio Dot is connected to the IRU through a dedicated LAN cable and remotely powered by PoE. As in Ethernet networks, the system employs a star topology, as opposed to the tree topology used in DAS. The ultra-compact design and use of LAN cabling simplify installation.

The design of the system is essentially a centralized baseband architecture that enables baseband resource pooling and full coordination. Initial baseband capacity can be selected to meet near-term demand, and more capacity can be gradually added at the DU and IRU as traffic demand increases –without any need to modify the cable infrastructure and the installed Radio Dots. To illustrate this point, a single cell per IRU can be upgraded to a multiple cell per IRU simply by exchanging the IRU – leaving the Radio Dots untouched. In addition, a 4x4 MIMO can be supported without changing the installed cable infrastructure.

The system is manageable all the way up to the antenna element. The radio properties of each individual Radio Dot can be tuned in terms of coverage and performance. The approach used in this solution reduces the need for careful, tedious and costly site investigations and network planning for each building, by applying rule-of-thumb-based network planning to define the deployment requirements such as inter-radio distance per building type (based on statistical simulation results for typical floor plans). This approach simplifies the planning process and is sufficient to guarantee high performance for most buildings. If needed, additional radios can be installed at a later stage, and this can be completed quickly due to the simple deployment and LAN-like star topology of the system architecture.

The ability to apply combined-cell technology to the maximum results in fully coordinated cells, which in turn further optimizes capacity, mobility and robustness of the indoor radio network. Combined cell minimizes the number of handovers by allowing multiple radios to share the same physical cell identity. It also increases peak rates, as control channel pollution can be avoided. The combined cell approach can be taken one step further by introducing SDMA, which allows resources to be dynamically reused within the cell. This enables instantaneous scale-up to full capacity, while minimizing the mobility overhead.

FIGURE 4 **Main-remote RBS block diagram**



The cable interface

Figure 4 illustrates the basic block diagram of a conventional main-remote RBS solution. Adaptation of this solution for indoor environments was a key design goal of the RDS, and our idea was to utilize cost-effective LAN cables to enable a totally fronthaul-based architecture. The challenge then, was to identify where the LAN cable interface should be introduced.

Using existing Ethernet technologies, such as 1000BASE-T or 10GBASE-T, to transport CPRI over LAN cables is one way to answer this question. However, Ethernet PHYs with IEEE1588v2 support were not originally designed to support CPRI with stringent requirements for bit-error-rate, latency and delay variation. This results in a compromise between bit rate, reach and latency. To address this, significant CPRI frame compression is needed, which increases complexity but also power consumption. Currently, the combined processing and compression for Ethernet PHYs and CPRI result in relatively high power consumption, and so due to the heat dissipation, this approach is not a good fit for a slim design.

So, what other options are available? LAN cables are capable of transporting very high bandwidths; for example, the effective bandwidth for 100m of Cat 6a per used twisted pair is between DC and 400MHz. This high bandwidth is feasible, as it operates in the lowest part of the spectrum and has both a low noise floor and rather low cable loss. As four twisted pairs are available for each LAN cable, the question now becomes: is it possible to efficiently exploit this bandwidth and the four pairs for fronthauling?

If we take another look at the RU design in Figure 4, an interface with a low intermediate frequency (IF) exists between the ADC/DAC blocks and the down-/upconverters. So, is it feasible to transmit the IF signals directly over the LAN cables? The answer is yes. As shown

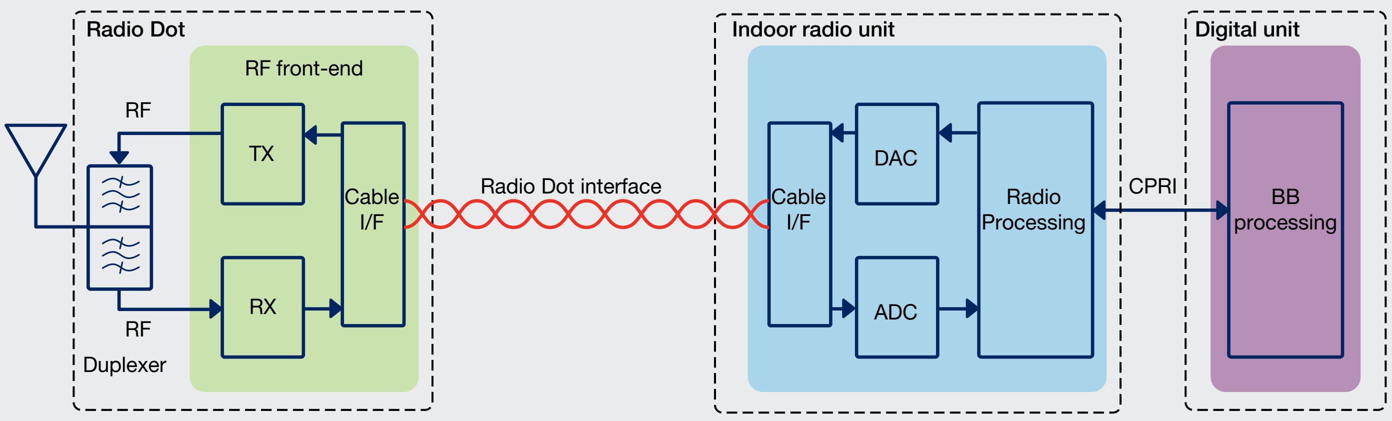


FIGURE 5 Radio Dot System block diagram

in **Figure 5**, such an IF-based design, in effect, extends the RF front-end over a LAN cable using an IF interface – which transports the radio signals at low frequencies with graceful capacity degradation in the event of unexpected cable faults.

The elegance and simplicity of this design requires minimal hardware/software changes regarding radio front end and processing, and enables the overall ultra-compact design (see Figure 3). The IF-based design requires a lot less power compared with possible Ethernet-based methods, as the IF cable interface can be designed in a more power-efficient way. In addition to the radio signals, the same twisted pair can carry synchronization signals and control signaling and power. This design also supports advanced features for cable equalization, AGC, cable testing and troubleshooting.

The IF-based design provides high radio performance and support beyond the standard LAN-cabling reach of 100m. Given the low noise floor and rather low cable attenuation at selected IF frequencies, 3GPP uplink and downlink requirements can be fulfilled, and 4x4 MIMO can be supported by utilizing all four pairs of the cable. Previous research has shown that the use of four antennas for indoor environments has great potential to further increase capacity[7].

Copper is the medium of choice for indoor broadband infrastructure and will remain so for many years. LAN cable technology has evolved significantly over the past four decades – from Cat 3 to Cat 7 and the upcoming Cat 8 – driven by improvements in Ethernet speeds from 10Mbps to 10Gbps and set to reach 40Gbps in the near future. This has led to substantial improvements in cable technology, which offer higher bandwidth and lower noise. The RDS will continue to build on this evolution, both for performance upgrades and cost erosion due to economies of scale.

Lab test results

The performance of the system has been verified in lab tests. **Figure 6** »

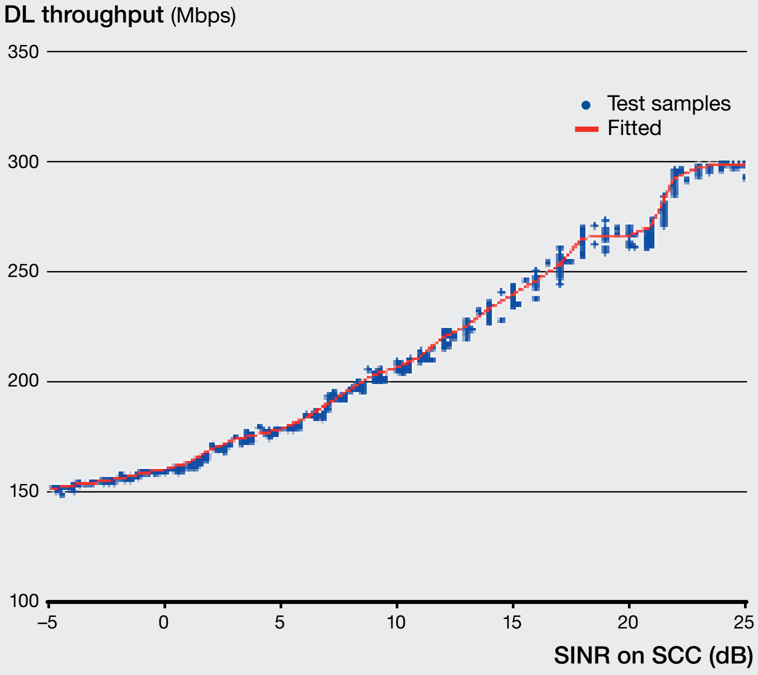
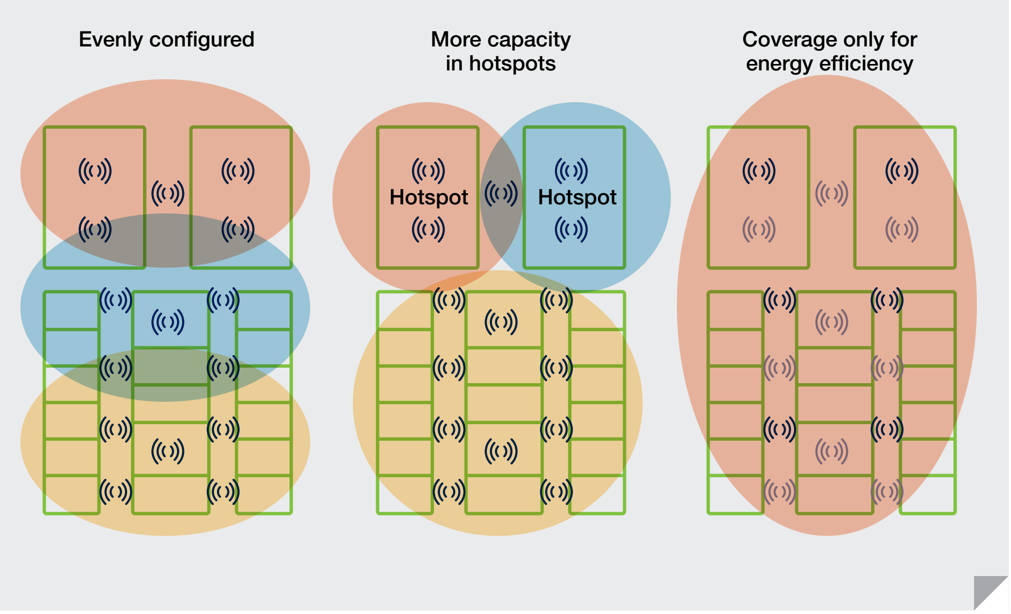


FIGURE 6 System performance

FIGURE 7 **Illustration of flexible capacity**



» shows the result of a DL test with carrier aggregation of two 20MHz LTE carriers in the 2.1GHz band and using 2x2 MIMO. The IRU and Radio Dot were connected using 190m of Cat 6a cable. The SINR on the primary component carrier (PCC) was fixed at 27dB to show the full peak rate of carrier aggregation, while the SINR on the secondary component carrier (SCC) was varied between -5 and 25dB. During the test, the DL throughput on the PCC maintained the expected peak rate of 150Mbps throughout. Figure 6 shows the aggregated DL throughput versus the SCC SINR, where the throughput increase above 150Mbps is due to the SCC. The aggregated peak rate of 300Mbps was achieved at about 23dB SINR.

Evolution to flexible capacity

Indoor traffic demand tends to vary over time and space, particularly in enterprise and public environments. For example, traffic demand regularly increases over the course of a day in areas where many people gather, such as in conference rooms, cafeterias, and lobbies. This high traffic demand disappears once people leave. Evenly distributing high capacity in a building for its peak use is not the best approach, as this tends to result in overprovisioning capacity.

As the RDS uses centralized baseband architecture, it can provide capacity in a more flexible way – by shifting available capacity from one place to another on demand. This can be implemented through dynamic cell reconfiguration (such as, traditional cell splitting and combining) or by using combined cell SDMA technology. For LTE Rel-10/11 UEs, combined cell SDMA is the desired approach for dynamic SDMA operations in one cell involving all the radios. This approach enables efficient use of the available baseband capacity, optimizing both network capacity and mobility, resulting in an improved user experience. Overlapping radios can be turned off (dynamically) to save energy. **Figure 7** shows three typical scenarios assuming three-cell baseband capability. Here, for illustration purposes only, a dynamic cell reconfiguration approach is used.

In the first scenario, three cells are distributed evenly to cover the indoor area, and each cell contains five radios. The second scenario covers the same space but includes two traffic hotspots. Here, the top cell is split into two smaller cells to provide higher capacity to the hotspots, while the rest of the area is covered by a single larger cell using the remaining baseband resources. In the third scenario, traffic demand is very low – a common situation late at night and early in the morning. To provide capacity for this low traffic scenario, the orignal three cells are combined into one large cell with only the selected radios active. All other radios (including the baseband resources involved) are inactive to save energy.

Summary

In this article, we have highlighted the challenges related to radio capacity and performance inside buildings, summarizing the main requirements to be successful in overcoming them. With a limited technology toolbox available to operators today, scalable growth for the platforms of the Networked Society is restricted, and so innovative design principles for smart and flexible small cell radio technology are needed.

Our aim was to provide operators with the best combination of two worlds: superior radio technologies and their continual evolution from the mobile industry, together with the well-established LAN building practices of the IT community. This was our inspiration for the design of the Radio Dot System – a novel indoor small cell solution. ❖

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