Evolution of Mobile Base Station Architectures

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Abstract - **With the proliferation of wireless standards such as GSM/EGPRS, WLAN, WiMAX, WCDMA, HSDPA/HSUPA, and WiBRO — future wireless radio base stations will need to support multiple air-interfaces, frequency bands and modulation formats. Radio technology that enables reconfigurable hardware across multiple standards is a big challenge for base station developers. In this paper base station architecture evolution towards full software defined radio technologies is analyzed.**

Key Words – **Base station architectures, software defined radio, baseband signal processing**

I. INTRODUCTION

Wireless communication standards are evolving rapidly. The key concern is mobile network topology and its dependence on radio equipment that is expensive and difficult to upgrade. In mobile networks, radio equipment is located within the base stations (BS) that are widely distributed throughout the network. Network operators must repopulate these base stations with new radio equipment, or install new ones, each time they want to introduce the new frequency band, add capacity, improve spectral efficiency, upgrade technologies or add new services. Number of various technologies providing an efficient and comparatively inexpensive solution to the problem of building multi-mode, multi-band, multi-functional mobile radio base stations can be summed up in term *software defined radio* (SDR).

No single SDR definition exists. Typically it is considered as sum of hardware and software technologies in which essential parts of operation can be reconfigured by the upgrading of its software. Other terms used in the context of programmable or reconfigurable mobile systems are: multi-standard terminal, cognitive radio, reconfigurable radio and flexible architecture radio.

The technology is promoted by the US Department of Defense to replace number of single protocol – radios with a common platform that could be reprogrammed to ensure interoperability. In military context benefits of SDR are obvious: ad hoc changes not only scrambling/encryption codes but also modulation scheme, data rate, channel bandwidth. To develop standards for US government equipment, the Joint Tactical Radio System (JTRS) project has been created. JTRS started in 1997 to replace approximately 750 000 military transceivers with 250 000 SDR radios. During the years, the scope of JTRS has been expanded to enable interoperability with the NATO and other "Allied Forces" radio systems [1,5].

In mobile communications software radio emerged as a "hot topic" in the early 1990's, when many people saw the technology as a solution to the problems of complex signal processing required in modern multi-mode/multi-band mobile terminals. Recently almost all the base station designs are evolved toward SDR architectures. In chapter 2 SDR categories are explained followed with enabling technologies described in chapter 3. Evolution of base-station hardware architecture toward SDR is analyzed in chapter 4 and 5.

II. SDR CATEGORIES

SDR Forum (International organization for promoting development and use of SDR technologies) has created five groups of software-radio categories (tiers). The first group (Tier 0) is **Hardware radio**. The second (Tier 1) is **Software-Controlled Radios** with only the control functions implemented in software. The base-band processing is performed with ASICs or fixed hardware. The third group (Tier 2) SDRs, called **Reconfigurable SDR**s, is most commonly used today. Mainly, software is used to control a variety of modulation techniques: wideband or narrowband operation, security functions and the waveform requirements of current and evolving standards over a frequency range. The fourth group (Tier 3) **Ideal Software Radio** has all of the capabilities of Tier 2 systems. Today it is the most advanced type of SDR that is achievable in the near future and it eliminates the analogue amplification or heterodyne mixing prior to digital-analogue conversion. Its programmability extends to the entire system, with analogue conversions taking place at the antenna, speaker, and microphones. The last group (Tier 4) - **Ultimate Software Radios** is defined by the SDR Forum for comparison purposes only.

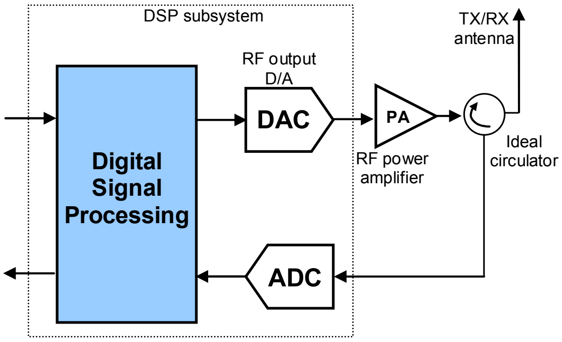

Fig. 1. Ideal SDR architecture

Figure 1 shows an ideal software radio where analogue to digital conversion takes place after the antenna and all subsequent processing is carried out in software. Conventionally circulator method is used for isolating the transmitting and receiver parts of the transceiver. The disadvantage of this architecture is that the entire RF spectrum is converted by the analogue to digital converter (ADC) making the specifications of this device (bandwidth, dynamic

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range and sampling rate) unrealizable with today's technologies. All the main functions are carried out in software including the RF and IF processing of the signals, followed by the baseband functions such as modulation/demodulation. Although the ideal software radio may currently be impracticable, it should be noted that many functions in today's handsets and base-stations are implemented as software code and not as hardware parts. These can be considered as practical software radios.

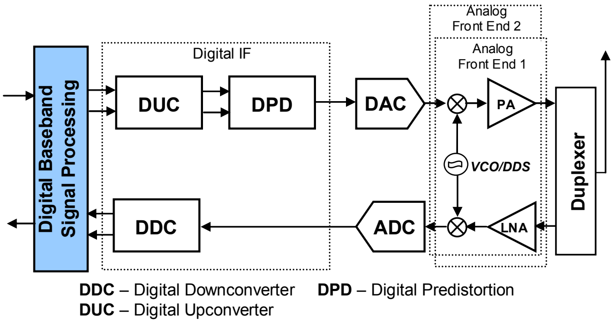

Fig. 2. Current-generation SDR architecture

The general hardware design of a today's SDR-based base station that can be reconfigured to support multiple standards is shown in Figure 2. The analogue-to-digital converter and the digital-to-analogue converter (DAC) operate at intermediate frequency (IF) and separate wideband analogue front ends are used for subsequent signal processing to the RF stages.

Digital IF extends the scope of digital signal processing beyond the baseband domain out to the antenna. This increases the flexibility of the system while reducing manufacturing costs. Digital frequency conversion provides greater flexibility and higher performance (in terms of attenuation and selectivity) than traditional analogue techniques.

The 3G standards and high-speed downlink packet data access (HSDPA) employ non-constant envelope modulation techniques such as QPSK and 16QAM. This places strict linearity requirements on the power amplifiers. Linearization or Digital Pre-Distortion (DPD) technique that can improve power amplifier efficiency usually is implemented in digital domain. DPD techniques have been developed to enable lower cost RF power amplifiers to be used instead of expensive, highly-linear power amplifiers. The non-linearity that exists in the lower cost power amplifier is artificially corrected by using adaptive filter functions in the digital domain.

Adaptive baseband digital DPD is a mature technology that has moved from research labs into deployed products. When combined with advanced peak power reduction algorithms, DPD significantly improves efficiency compared to the feed-forward PAs. For WCDMA four-carrier operation, power efficiency of the transmitter chain (that is, transceiver and power amplifier) can be improved from typically less than 10% to around 18%. Power efficiency has an environmental impact and affects operating costs. Lower power consumption can reduce costs for energy and reduces the demand charge (contract ampere). DPD technology enables the active radio parts of the BS to be integrated into a complete radio unit (RU) with digital baseband input signals.

With DPD, the PA curve is forced to have a linear response over a specific operating range. Figure 3 shows a block diagram of the complete DPD system [7]. Before entering the DAC, samples of the baseband input signal are multiplied by complex coefficients drawn from the lookup table. The coefficients, which implement the predistortion function, are updated according to changes in PA behavior relative to changes in traffic, environment, and aging effects.

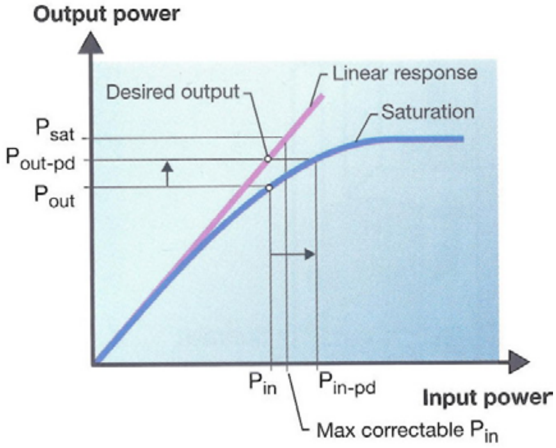

Fig. 3. Digital predistortion principle

In digital up conversion (DUC), the input complex baseband signal is sampled at a relatively low sampling rate, typically the digital modulation symbol rate. The baseband signal is filtered and converted to a higher sampling rate before being modulated onto a direct digitally synthesized (DDS) carrier frequency [2]. The DUC typically performs pulse shaping and modulation of an intermediate carrier frequency appropriate for driving a final analogue up converter (Figure 4).

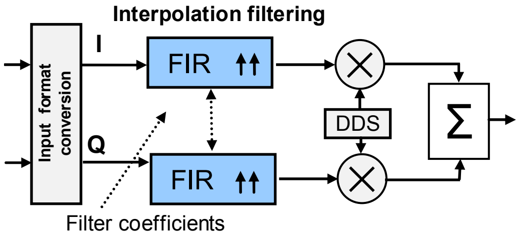

Fig. 4. Digital Up Converter (DUC)

On the receiver side, Digital Down Converter (DDC) is used to perform channel access functions. It has a configurable signal-path comprising a multiplier, a DDS and decimating filter. The decimating rate could be changed. In Figure 5 block diagram of a DDC is shown. RF signal from ADC is multiplied with periodical (sin/cos) signal generated in DDS and spectrum translation to baseband is performed. With decimating filters desired baseband signal is filtered and converted to lower sampling rate before being send to common DSP platform.

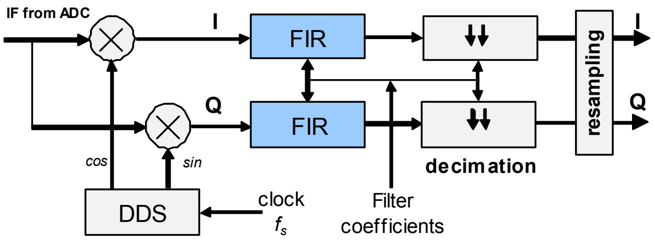

Fig. 5. Digital Down Converter (DDC)

Translation of digital IF signal to baseband is shown in picture below.

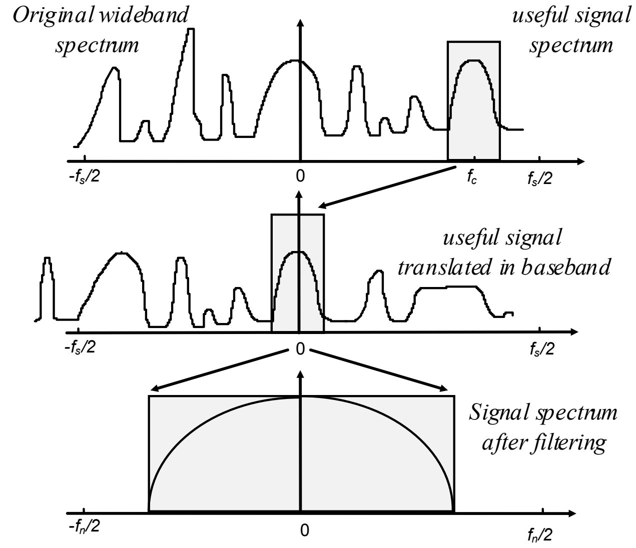

Fig. 6. DDC signal down translation.

III. SDR ENABLING TECHNOLOGIES

The semiconductor technologies enabling SDR systems are ADC/DAC, digital signal processors (DSP), field-programmable gate arrays (FPGA), filters, and RF amplifiers.

The ADC is the most critical element of an SDR since its speed determines how close to the antenna the analogue-to-digital conversion can be performed. ADC performance is defined by three measures: speed (number of samples per second), resolution (the number of bits into which each sample is coded), and linearity (how accurately the digital output codes follow the analogue input values over the range of service). The fastest ADCs today in commercial use, acquire analogue signal with approximately 10 GHz sampling rate. For use in wireless applications these components are too expensive, and consume too much power to be considered. An ADC priced low enough and with enough resolution for use in mobile devices can acquire about 200 MSPS, which is a high enough sample rate to digitize the IF section of the transceiver (sampling the full IF mobile band and extracting individual channels in the digital domain) but it has no performance required to digitize the entire RF band.

The digital signal processor (DSP), a processor optimized for performing arithmetic calculations at high speed. It is the fundamental building block of SDR base stations and has been certainly the original enabling technology for SDR. DSPs provide spreading, de-spreading, modulation, demodulation, and filtering functions, and can usually implement many radio interfaces at the same time.

Field programmable gate arrays (FPGAs) are programmable devices whose interconnect and logic functions can be redefined after manufacture, with the ability to custom program and reprogram the component's function. There are a variety of FPGA architectures, some of which can be very sophisticated, including not only programmable logic blocks, but programmable interconnects and switches.

IV. SDR BS ARCHITECTURE

A typical base station (Figure 7) has four main modules: radio frequency (RF), baseband, control and transmission. The RF module receive/transmit signals and converts them from/to digital data. The baseband module processes the encoded signal before transmitting/receiving it from/to the core network through the transmission module. Coordination between these three functions is maintained by a control module. Several reference points (RP) has been defined with the industry focus in achieving lower cost of different modules. Example of SDR base station is shown on Figure 8.

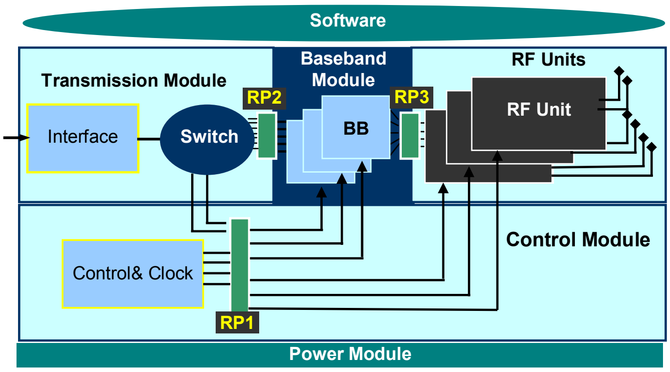

Fig. 7. Base-Station Architecture

In cases where different technical processes require the same or similar types of resources it is advantageous to concentrate the available hard- and software in a pool and thereby maximize the efficiency of resource usage. Pooling of resources yields a capacity gain in such environments, where an inhomogeneous distribution of resource demands can be expected. This is also true for mobile radio BS.

Concentration of baseband resources in one place enables signal processing resources to be shared between cells maximizing the efficiency of BS processing capacity usage. Another important aspect of pooling is the inherent redundancy of resources that share the same pool. In the case of radio base stations it means that the traffic demand can be taken over by other resources within the pool, when a part of the total capacity resource becomes unavailable. Consequently, the availability of resources for traffic handling is increased as compared to the non-pooled resource case.

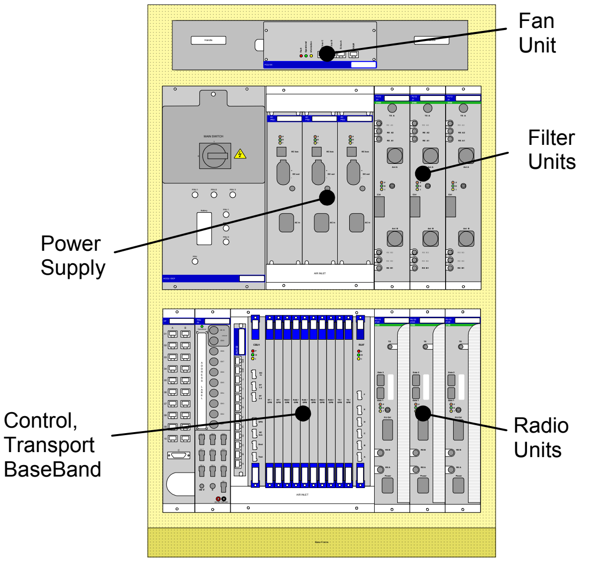

Fig. 8. WCDMA Ericsson Base-Station modules

The following two different types of resources pooling can be identified for base stations:

1. resource pooling over different sectors (cells) of the same base station,
2. resource pooling over different frequency layers of the same base station.

As a consequence, the same total BS capacity can be provided with fewer assets than if the resources for the different sectors would have been separated from each other. The total pooling gain [6] in a base station can be further increased, if the hardware architecture allows for a pooling not only over different sectors, but also over different frequency layers of a base station (Figure 9).

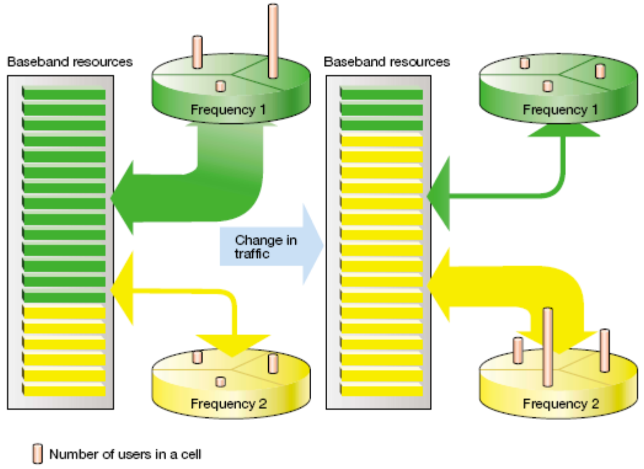

Fig. 9. Baseband capacity pooling

In 3GPP standards term “channel element” is introduced to measure virtual signal processing capacity of BS. The channel element (CE) describes the capacity resources required for users with a specific service, so it can be recognized as base station hardware capacity. The number of channel elements is based on traffic type, and is dependent on radio bearers used as well as on the number of the simultaneous users for specific radio bearer.

Although the CE is a resource equivalent not standardized by 3GPP and thus in not defined equally by different manufacturers (the definition differs in how many CE are required for a given service, whether CE resources are required for common signaling, compressed mode measurements, and so on), it represents a simple and intuitive measurement of baseband capacity.

Power amplifiers and RF modules usually account nearly 50% of the BS cost and manufacturers are now working on integrating those two functions into a single lower-cost module resulting in initiatives such as Common Public Radio Interface (CPRI) and Open Base Station Standard Initiative (OBSAI) to define and agree on base station architecture at the modular level.

CPRI works to devise an RF module standard interface in order to encourage alternative, competitive sources for RF modules and PAs. Similar to CPRI, OBSAI defines open interfaces at multiple reference points within the base station architecture, with reference point 3 (RP3) representing the RF front-end to baseband processing interface.

The OBSAI RP3 specification defines the interface between the baseband module and the RF module. The specification allows for a maximum of 9 pairs of unidirectional links for every baseband and RF module. For a typical BS, those links can be connected with a mesh or a centralized combiner and distributor (C/D) topology. The C/D topology is more suitable for a large BS, as it can be managed more easily than the mesh topology. The latest work by OBSAI on RP3 is a RP3-01 extension. It specifies the RP3 interface protocol for remote RF unit use. Figure 10 shows the reference architecture of a BS with remote RF units.

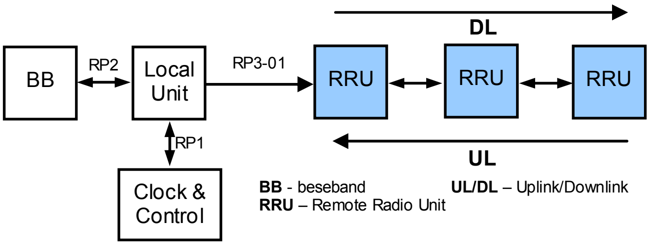

Fig. 10. OBSAI remote radio unit architecture

V. EVOLUTION OF BASE STATION ARCHITECTURES

The base station architecture is moved from an essentially modulation-specific to a software-defined architecture. The recent move toward standardization of the internal BS digital interfaces, in OBSAI and CPRI initiatives, fundamentally modifies the BS production models. Those standardized interfaces give an opportunity for an original equipment manufacturer (OEM) to outsource both the baseband digital card hardware and the high-power RF transceiver hardware production [3]. This leaves the OEM free to concentrate on the complex application software and services, which are their key differentiators in many applications (Figure 11).

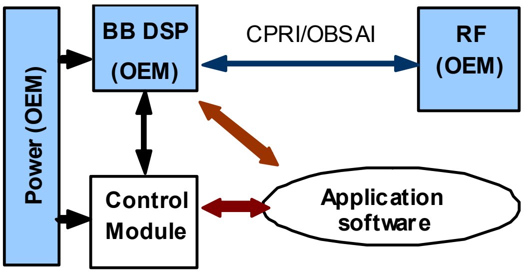

Fig. 11. New BS manufacturing model.

In a conventional base station, the baseband and RF sections of the transceiver are usually physically close to each other. However, the RF power is not being generated close to the antenna (its intended point of use), and a significant amount is wasted in cables. There are two alternative topologies which are enabled by the use of SDR: distributed base station architecture and orphaned RF networks (also known as "BS hoteling").

An example of the digital and RF units separation (distributed BS architecture) is the use of the RF transceiver (remote RF unit - RRU) at the top of the tower containing transmit and receive antennas, as illustrated in Figure 12. The remaining BS parts could easily be placed in lower-cost basement space, with a fiber-optic link between the two. This approach has a number of benefits over the more traditional approach of mounting the amplifier in a BS cabinet, since it eliminates high-power RF cable losses.

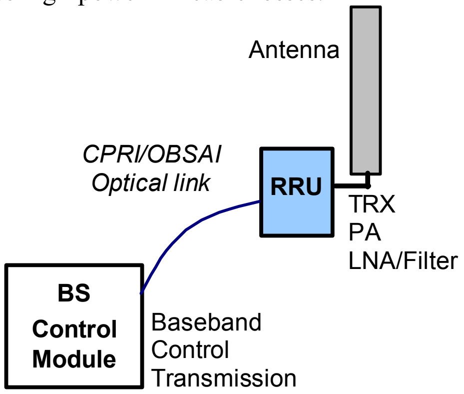

Fig. 12. BS architecture with separated RF and digital units

The concept of BS "hoteling" is illustrated in Figure 13. This is a network deployment in which the majority of the components of a traditional base station are housed in a central location (the hub). This hub can be placed at a convenient, low-cost location, for example, in the basement of a building or in an out-of-town industrial zone. This leaves a minimum of components that are required to be housed at the cell site.

All of the network components, interface elements, and so forth, as well as the baseband signal generation, modulation, demodulation, coding, and framing functionality are housed at the central base-station hub. The hub interfaces directly to the core network and derives all subscriber calls from there. It also generates and receives the modulated data samples required for transmission to/from the remote RF unit.

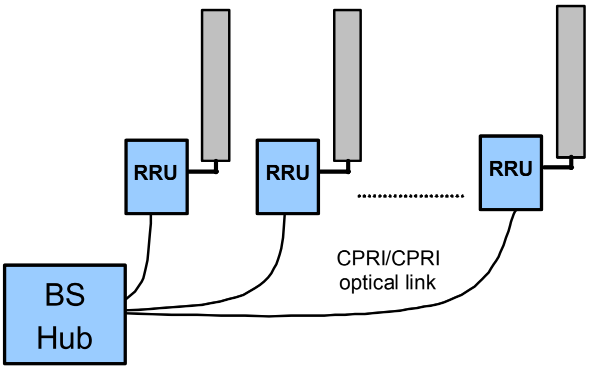

Fig. 13. BS "hoteling" architecture

Example of BS with orphaned RF architecture is shown on Figure 14. RRU can be placed 15km from the main BS unit (MU). Also, MU-RRU connection can be established by RRU cascading.

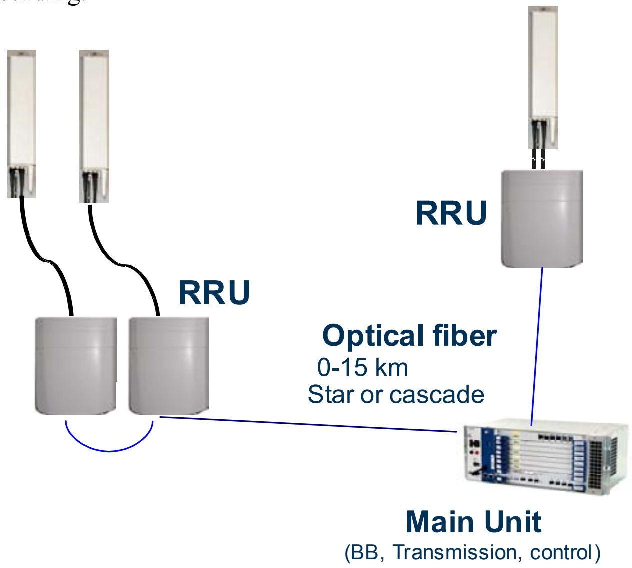

Fig. 14. Ericsson Base-Station with distributed architecture

Radio air-interface standards are continuously evolving to support higher data rates through the introduction of advanced baseband processing techniques such as adaptive modulation and coding, space-time coding (STC), beamforming, and multiple input multiple output (MIMO) antenna techniques. Smart antenna systems can bring significant benefits to mobile networks. These benefits are principally in the areas of improved interference cancellation and in enhanced system capacity. However, benefits come at an expense of the computationally intensive processing algorithms, multiple RF power amplifiers, feeder cables and calibration systems increasing the cost of this type of system (Figure 15).

Although adaptive antenna systems have been proposed and researched for some time, they have yet to achieve widespread acceptance. The advent of SDR architectures enables smart antenna base stations to be realized. This type of architecture assists in mitigating some of the cost, size, cabling, and calibration issues.

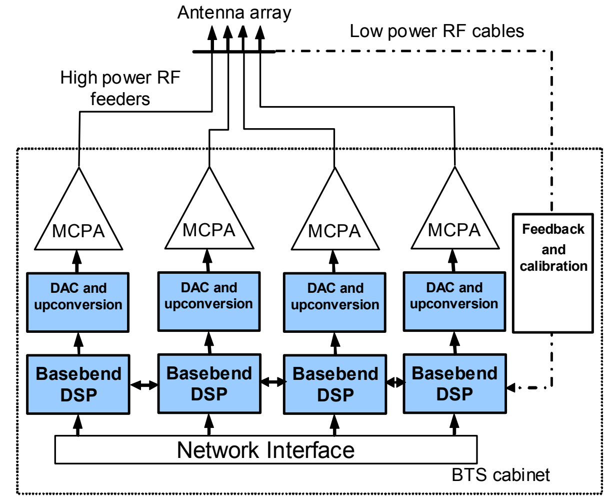

Fig. 15. Adaptive antenna downlink based upon conventional BS architecture.

Figure 16 shows downlink for BS with adaptive antenna array that uses SDR. Cost savings in MCPA (Multicarrier Power Amplifier) and cables are obvious.

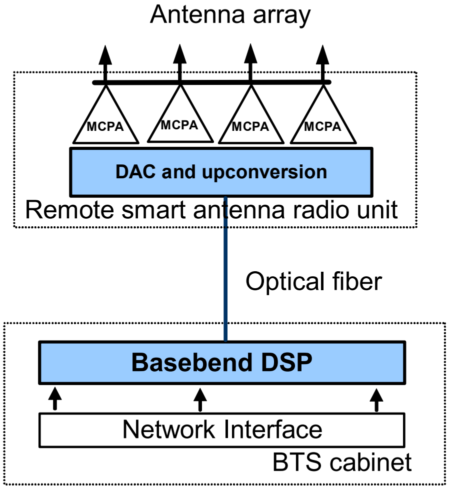

Fig. 16. Adaptive antenna downlink based upon SDR BS architecture.

In 3GPP Rel.6 base station (node B) handles the physical layer of the wireless access. Other nodes, such as radio network controller (RNC), serving GPRS (SGSN) node and gateway GPRS node (GGSN) handle radio resource management, mobility management, call control, session management and transport network optimization. In proposed architecture for long term evolution (LTE) network architecture, the functions of Rel.6 nodes GGSN, SGSN and RNC are divided between the single central node - access core gateway (ACGW) and base station.

A Flat-architecture radio access network combines the functions of a base station, RNC and GSN nodes into a single node. Base station becomes more intelligent node with additional network functions. The emerging BS must be able to grow to a much higher capacity than that of today's voice and data. In addition to the capacity requirement, the BS must provide flexible services and the multiplicity of connection protocols.

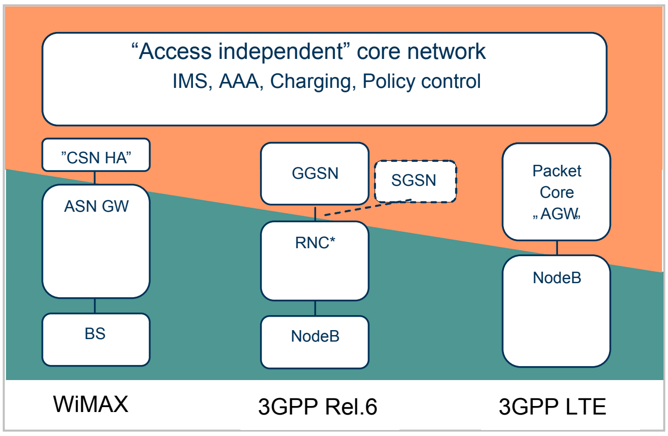

Fig. 17. Flat network architecture and BS functional evolution.

Future mobile network evolution into flat network is shown on Figure 17 and it is an important step on the path toward 4G type architectures.

VII. CONCLUSION

The use of software defined radio technique enables a number of new base station topologies. These topologies result in advantages for both the base-station manufacturer and the network operator, particularly in the areas of power consumption and cost. SDR technology affects not only base station architecture but also production models and network topology. Flat network architecture simplifies network deployments and eliminates the need to re-configure multiple hierarchical network elements each time a new BS node is added. On the other hand pressure on BS hardware and software flexibility becomes higher.

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