Open Wireless System Cloud: An Architecture for Future Wireless Communications System

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Abstract

Open Wireless System Cloud (OWSC) is a radio access network architecture for future wireless communication systems with remote radio heads, centralized wireless computation on open platforms, and cooperative wireless signal processing and management. With centralized wireless signal processing, system capacity can be increased using emerging wireless techniques, such as cognitive radio, or collaborative processing and coordinated multipoint transmission (CoMP). Centralized open computing platform provides greater flexibility as the system can simultaneously support multi-standards and services, such as 2G, 3G and 4G as well as multiple type wireless applications. With this open architecture, OWSC can serve as infrastructure for researchers and wireless resource provider and can be supplied by 3rd parties much like Amazon provides AWS today. The barrier to entry for new entrant wireless operator role is greatly reduced. This enables new business models for the future mobile networks and service providers.

Keywords: wireless communications, cloud computing, wireless architecture

1. Introduction

Imagine a day, not too distant in the future, a new entrant wireless service provider only has to: rent some frequency; rent some radio antennae; rent some cloud-based processing resources based on its specific requirements such as standards, coverage areas, number of subscribers and etc. Any company can become a wireless network operator.

The increasing popularity of always-connected devices such as smart phones and tablets, which provides constant access to Internet services, video, music and many other forms of digital content through the wireless network, brings ever increasing demands for bandwidth everywhere. For the existing mobile infrastructure, there are formidable challenges, such as ever wider geographical coverage, higher data rate, ubiquitous mobility support, distributed application awareness and distributed application processing and etc (Bonomi, 2010). At the same time, it presents an opportunity to evolve mobile networks. To influence the future, we have to understand the existing wireless networks.

1.1 Limited System Capacity and Low System Utilization

Radio access network is the most important part of the wireless communication system. It provides seamless coverage as the user moves between different parts of the network. As illustrated in Figure 1, for conventional radio access network, each base station (BS) is connected with several sectoral antennae and will only handle the signals within its coverage area. When the cell size gets smaller, capacity can be increased linearly with cell density. But as cell size gets smaller, radio interference between antennae limits system capacity. The traditional way of expanding capacity by splitting cells and adding carrier frequencies results in bottlenecks. Additional base stations cannot improve frequency utilization. Moreover, the average utilization of current base stations is quite low. The average load is much lower than that of peak load. In the residential districts, daytime voice traffic is light but evening voice traffic is heavy. In the business districts, the opposite is true. As it is impossible to load share computational resources across one base station to another, base stations are over engineered 60% of the time.

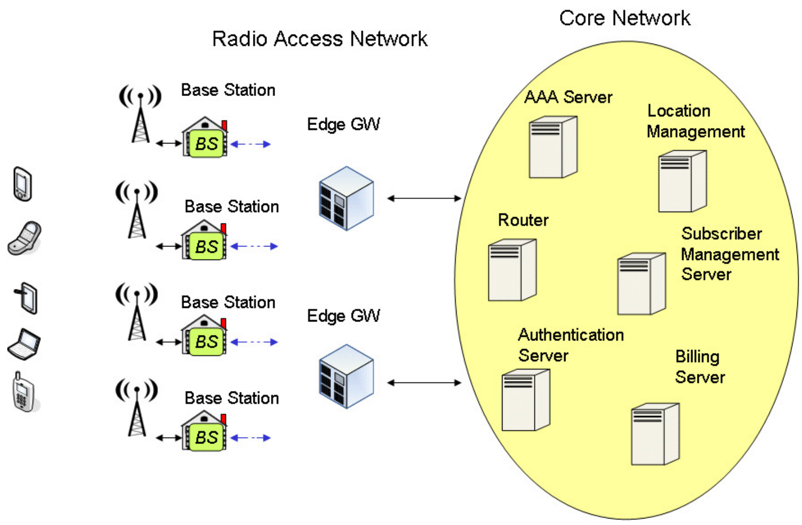

Figure 1. Conventional wireless communication system

1.2 Ever-increasing Maintenance Cost

Maintaining these networks whether in USA, Europe, India or China is tricky. Network maintenance must deal with complex signaling and RF management which are both tedious and expensive. About half of the capital cost for a new 4G network is spent on network equipment such as base stations. As telecom equipment is currently proprietary, whenever a network is upgraded, much of this equipment has to be replaced. Moreover, multiple wireless standards, such as GSM, CDMA, WiMAX, and LTE, require replicated systems. The coexistence of multiple standards is a reality that must be dealt with by all operators. Current proprietary solutions only support a single standard. The cost of ongoing network upgrade to support ever increasing number of protocols will become prohibitively expensive and complex. A different wireless paradigm is required.

1.3 Current Approaches

To resolve the above mentioned problems and to reduce the cost, network operators are trying different approaches. For example, to improve the coverage and capacity, some wireless operators such as Vodafone, AT&T and Verizon, who are also IPTV and wireline/DSL providers, have launched femtocell services. Femtocell is a low powered cellular base station, typically designed for use in a home or small business. It connects to the service provider's network via wired broadband. This fixed-mobile convergence (FMC) can reduce both capital expenditure and operating expense compared to the cost of a base station. However, the techniques rely on the broadband connection with the service provider's network. It can not address the problem of ever broader geographical coverage or high degree of mobility.

There are some emerging wireless technologies, such as cognitive radio, Coordinated multipoint transmission (CoMP) and CO-MIMO (cooperative multiple input multiple output). CO-MIMO, also known as Ad-hoc MIMO, utilizes distributed antennae which belong to other stations. Conventional MIMO, i.e. single-user MIMO, only employs antennae belonging to the local terminal. CO-MIMO improves the performance of a wireless network by introducing the benefits of multiple antennae, such as diversity, multiplexing and beamforming. This cooperative diversity can also be described as a form of macro-diversity, which can be used in soft handover. CO-MIMO is a technique useful for future cellular networks such as wireless mesh networking or wireless ad-hoc networking. It can improve wireless network capacity significantly. However, CO-MIMO requires collective processing of the physical layer data among different base stations. In existing radio access networks, equipments for base stations are typically located close to radio header and antenna. Since there are no high speed data connections amongst base stations, physical layer data streams of different base stations has to be processed locally. This is the main obstacle to use CO-MIMO in current wireless network structure.

1.3 Should the Cloud Be an Option?

Cloud computing has become a hot technology in recent years. Computational tasks, content storage and, even the applications are being moved into "the cloud". Architecturally, wireless communications systems and cloud computing shares important traits such as very large user base, broad geographical coverage and high aggregate throughput. These traits are shared with many cloud-based applications. Moreover, the mobile network of the future will entirely be IP-based which makes it easier for switching and processing. It would be beneficial if cloud-based techniques can be applied to wireless systems. There were some prior attempts to apply cloud-like ideas on wireless systems such as, in 2003, distributed wireless communication system (DWCS) (Zhou, Zhao, Xu, Wang, & Yao, 2003). Centralized processing is introduced to process received intermediate frequency (IF) signals from different base stations. These signals are transmitted to a data center through optical fiber and processed together. Due to hardware constraints and limitations of the existing implementation of its time, the proposed system was not possible. With the development of high speed hardware devices and ever increasing computation capacity, it is now feasible to extend wireless system to the wireless cloud. Back in 2010, China Mobile who operates the world's largest GSM network, put forth the concept of C-RAN (China Mobile Research Institute, 2010). The C-RAN system is a collaborative, real-time cloud radio access network. It is based on the concept of centralized baseband processing pools (virtual BTS pools), RRUs, and antennae.

In this paper, we explore in depth, the potential to use cloud-based techniques in wireless communications system and propose a cloud-based infrastructure for the future of wireless systems – Wireless System Cloud (WSC). Wireless network operators will be able to reduce capital expenditure for system deployment and upgrade. Network operators will be able to shorten time to market of new services and applications. WSC can be supplied by specialist 3rd party, like Amazon is supplying AWS. Barrier to entry for new operators is greatly reduced. The vision described at the beginning of this paper is possible. It will open up new business models and opportunities for wireless providers, whether incumbent or new entrant.

2. Overview of Wireless System Cloud

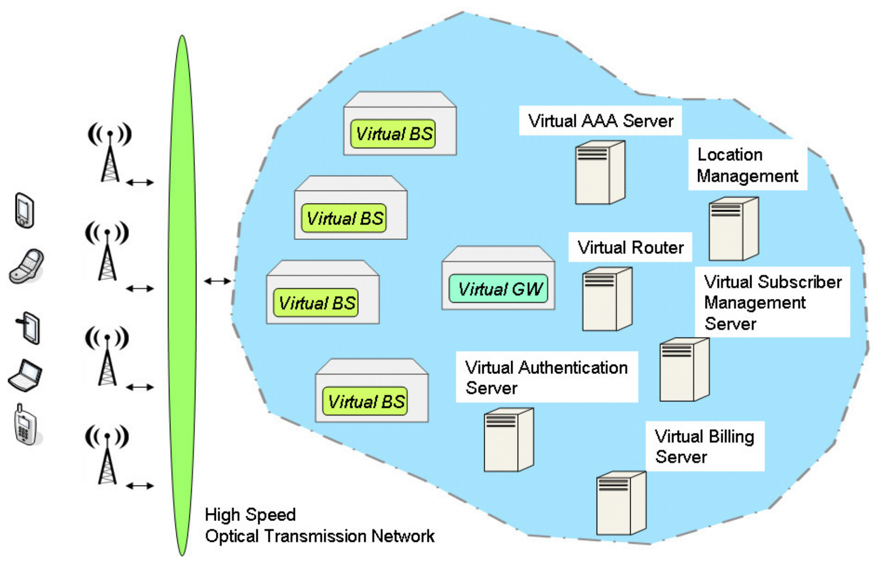

Figure 2. Open wireless system cloud

As illustrated in Figure 2, most of the functions of the wireless network will migrate to the open cloud. The wireless signal-processing of the base station are handled by the Open Wireless System Cloud (OWSC) framework as well as related management functions in the core network. The virtual base stations (VBS) in the cloud replace the traditional base stations. The remote radio header (RRH) is used to decouple the radio header from the base station. The radio header is equipped with a transceiving device as well as digital/analog (D/A) and analog/digital (A/D) converters, which convert radio frequency (RF) to digital intermediate frequency (IF) signals. IF signals from different base stations are backhauled to the computing center using optical fiber. A direct or one-hop connection to an optical network is provided for each radio header. There are several ongoing standards which define the transmission protocols between RRH and BS, such as Open Base Station Architecture Initiative (OBSAI) and Common Public Radio Interface (CPRI). System upgrade becomes a software upgrade. Deployment is much simpler. New protocols or improvement in existing protocols can be deployed very quickly and with low incremental cost. This structure matches the evolution of the Internet. The hierarchical structure of traditional networks is being flattened by the cloud. The distance of the optical backhaul between the RRH and the cloud computing center would be determined by the size of the centralization scale. Since the cost of the fiber network is reduced significantly nowadays, the cost to provide the optical backhaul is realizable. Actually, in current wireless network deployment, the optical backhaul is also the technical trend.

This proposed infrastructure is based high performance software defined radios (SDR) running on commercial off the shelf (COTS) platforms in the cloud. In a cloud computing center, SDR provides all the expected functions of a wireless access network, such as modulation/demodulation, channel coding/decoding, joint detection, channel measurements, medium access control (MAC), link layer control (LLC), radio link control (RLC), radio network control (RNC) and etc. Almost all of these computing tasks are implemented by software on N-core general-purpose processors utilizing high degree of parallelism and specially designed accelerators. Scalable computing cluster with SDR implementation makes it feasible for cooperative wireless signal processing amongst the virtual base stations. The resulting gain in multiplexing and diversity is not possible on standard base stations.

The concept of cloud computing has been used for many applications, but there has been very few attempts in the wireless computing domain. Wireless communications system has its own characteristics, such as latency sensitivity, QoS guarantee requirements, as well as all the associated complexity and performance trade off. In the proposed OWSC, RRH technologies make it possible to backhaul all the individual base stations' signal to centralized location. Software radio technologies enable software processing on standardized COTS platforms. Cloud-based computing center provides the capability for resource balancing as well as enable visualization and cooperative computing. Different wireless protocols and services can execute on the same physical infrastructure with open IT platforms. In the following sections, the technological components of the OWSC are discussed in detail.

2.1 Radio Signal Transmission

Figure 2 is the abstract OWSC system diagram. The radio front end (RFE) is composed of antenna, antenna tower and RRH. In current systems, the A/D and D/A converters are embedded in RRH and the interface between RFE and BS is digital. Over the last few years, the wireless system manufacturers has worked together to define standards for this interface between the RFE and the BS, namely OBSAI and CPRI. The standardization of this interface will enable the RFEs and BSs from different manufacturer interconnect and interwork with each other.

More importantly, these standards are specially designed for high performance remote signal transmission. This means they are well suited to be used as the link level transmission for centralized wireless computing. CPRI is more popular in current practical deployment. CPRI is proposed to be used with some modifications to support switching mechanism which is needed to load balance across a "cloud". These Internet-based protocols carry CPRI data over optical links and supports different switching topologies between RFEs and OWSC's VBS pool.

It is important to note that the link between RFEs and VBS pool is characterized by high data throughput. For example, if the target throughput is 20Mbps for both uplink and downlink, 8-bit DAC, 1/2 coding rate and 16QAM are used, the downlink data rate to RFE is about 658Mbps (Chen, Wang, & Lin, 2009). If three sectoral antennae are supported for this VBS, the overall downlink throughput is about 1.975Gbps between the RFE and the VBS pool. High speed optical fiber transmission techniques are used between VBS and RFE to achieve this level of throughput. On the VBS side, special hardware accelerators are used to sustain the required throughput.

Timing and synchronization are critical for wireless systems. Accurate timing information is need for handsets. Reliable handover between BS requires very accurate clock synchronization. In time-division duplex (TDD) system, all the transmitters are required to synchronize their uplink and downlink time slots to reduce interference. For all the BSs and RFEs, there are strict timing requirements so they share the same timing clock. For example, for GSM, WCDMA and CDMA2000 systems, the frequency accuracy is 0.05 ppm at air interface. For the time synchronization, the accuracy should be within +/- $3\mu s$. In the worst case scenario, the clocks should be synchronized to within +/- $10\mu s$.

In the proposed OWSC, the timing and synchronization mechanism is composed of 2 parts: a master timing server and a timing network. The timing server generates accurate timing information, and the timing network distributes the precise timing signal throughout the OWSC system. In IP-based cellular network, the existing Ethernet/IP network can use the backhaul connection to access the network operator's reference clock. However, the accuracy is problematical due to non-deterministic packet delays inherent in Internet protocols. In order to manage the non-determinism, protocols such as IEEE 1588 which specifies the use of PTP - Precision Time

Protocol can be used. For the timing server, GPS is widely used in the wireless system as a very accurate source of timing. In some of femtocell solutions, GPS timing with IEEE 1588 PTP has been adopted for system synchronization. In OWSC, we propose to use the same mechanism to synchronize the whole network. GPS modules are cheap and easy to embed in the master clock server. IEEE 1588 interface can be easily embedded in the RRH and BSs with dedicated chips or FPGAs. Thus, the two main challenges for radio signal transmission - high I/O throughput between RFE and BSs and highly accurate clock synchronization - are solvable.

2.2 Wireless Signal Cloud Computing

Wireless access network is characterized by high computation complexity in baseband signal processing. In the proposed OWSC system, the high computation load for the baseband processing is handled in the cloud-based computing center. In this section, we will introduce how OWSC can meet the computation requirements of future wireless system.

In a typical BS, baseband processing consists of two layers: the PHY layer and the MAC layer which have different computation complexity. PHY layer and MAC layer will normally consume most of computation resources. The remaining computational resources are consumed by the interfaces and middle layers.

PHY layer is computation intensive due to complex vector and mathematical computing. MAC layer handles packet and protocol processing which requires highly efficient multithreaded, multitasking architectural support. In OWSC, since the requirements of PHY layer and MAC layer have orthogonal computational characteristics, they can be executed on different platforms with different architectural level support. In OWSC, the processing of PHY layer and MAC layer are both handled in the cloud with high performance SDR implementation.

To evaluate the feasibility of using cloud computing for wireless processing, a series of experiments have been done on several different IT platforms, such as Intel x86 blade server and Cell/B.E. blade server (Chen, Wang, & Lin, 2009). The testing protocol is WiMAX (802.16e), all the modules in Figure 3 are implemented with vector engine acceleration. 16QAM modulation, 1024-point FFT and 2x2 MIMO techniques are used. 1/2 rate convolutional code and Viterbi decoding are used for channel coding/decoding. For general purpose IT platforms, there are several parallel computing technologies which can be used to provide high performance, such as multicore, multithread and SIMD instruction.

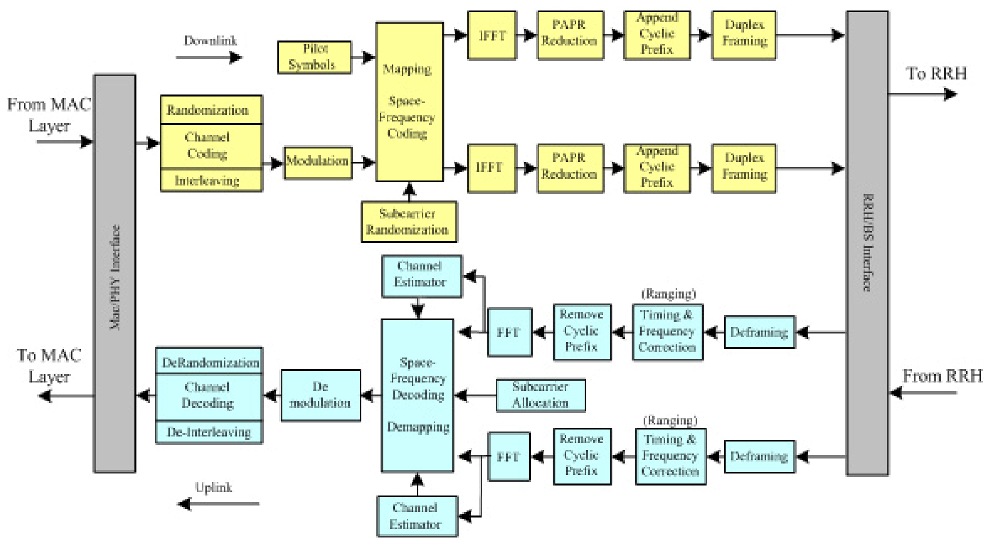

Figure 3. WiMAX physical layer diagram

On IBM QS21 (with two Cell/B.E. processors), the blade server can support 60Mb/s data throughput for both uplink and downlink with a well designed configurable framework (Chen, Wang, & Lin, 2009). For x86 platform, Intel Xeon(R) blade server X5355 is used which has 2 quad-cored CPUs clocked at 2.66GHz. The computational complexities of each optimized modules are illustrated in Figure 4. With the multicore and multithread architectural support, much higher throughput can be achieved. In our experiments, with 8 cores in one cluster, about 200Mbps and 45Mbps throughput can be achieved for BS transmitting and receiving separately. The most computational intensive modules amongst wireless baseband processing modules are channel coding/decoding, such as Viterbi decoding, turbo code decoding and low-density parity-check (LDPC) decoding.

In a software implementation of WiMAX and LTE, the turbo code channel decoding will use more than 50% of the overall computation resources. This has been evaluated on IT platforms (Tan, 2009). Due to high inter-dependency amongst the bits and iterations, the turbo decoding algorithm is very difficult to parallelize and cannot take advantage of evolving general-purpose processors architecture. A well optimized software turbo decoder (with 6 times iterations) cannot provide more than 20Mbps throughput nor meet the throughput requirements of realistic systems. There is a large gap between the software implementation and hardware solutions. The high computation complexity of channel decoding is the main obstacle for the software implementation of virtual BS.

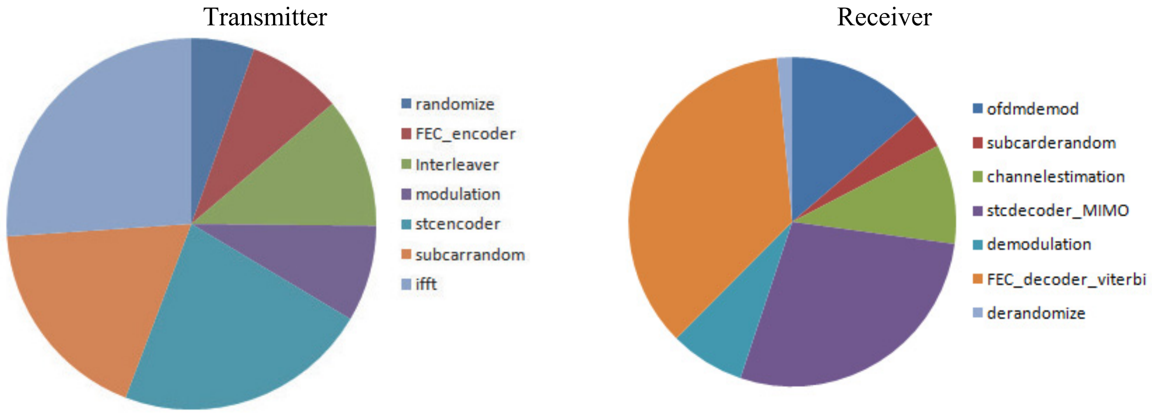

Figure 4. WiMAX BS physical layer modules computation complexity

We propose to use FPGA or ASIC to build up a decoding matrix which is responsible for all decoding tasks. The virtual BS in OWSC is illustrated in Figure 5. The decoding tasks from different PHY in different virtual BSs are packaged into decoding tasks with different attributes. The decoding matrix manager will dynamically distribute the decoding tasks to different decoding units based on different latency and bit error rate (BER) requirements. The matrix can be composed of heterogeneous decoding units (software implementation on CPUs with different clock rate or ASIC/FPGA) to meet requirements from different wireless standards, connections and applications. The virtual BS has the choice of using either modifiable software or high efficiency hardware. With only a few channel coding algorithms in current wireless standards, the decoding units can be designed with uniform interfaces and the decoding matrix can be used for different wireless protocols simultaneously.

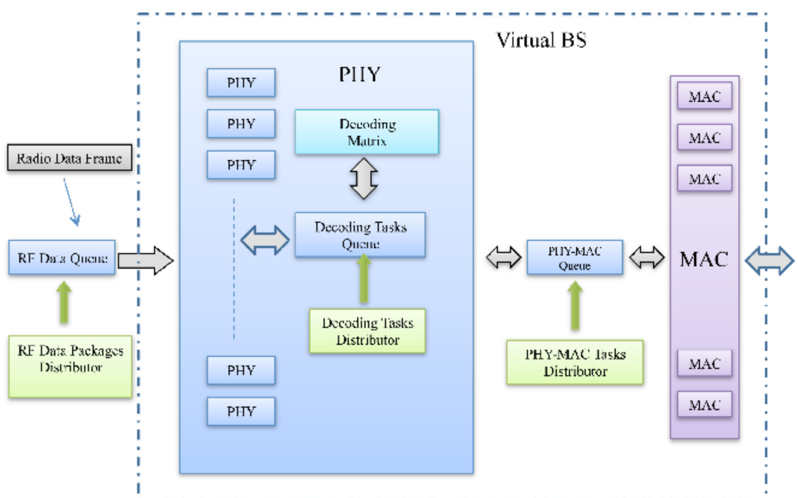

Figure 5. Virtual base station

2.3 QoS Guarantee and Real-time System Implementation

Since wireless baseband processing is inherently parallelizable, cloud-based parallel computing techniques can readily be applied. Firstly, if the links from different BSs are independent of each other and no cooperative processing is required, they can be processed on different computing nodes. Secondly, within a BS, parallelism exists between different uplinks and downlinks on different sectors which can be exploited. Since there are no data dependencies between the links, processing for each link can be assigned to computing kernels with enough resources. Thirdly, even within a link, downlink and uplink transmissions are packaged into radio frames with fixed duration. For example, in the LTE PHY, each frame holds 10ms of data. These radio frames can also be processed on different computing nodes separately with shared link level context. Lastly, in the radio frame processing (PHY and MAC), SIMD vector processors on modern CPUs can be used. The high degree of parallelism permits the processing tasks, grouped with different granularities to be distributed to different computing nodes.

To meet the real time requirements of wireless communication systems, hierarchical task dispatchers are used. All tasks are annotated with the wireless system attributes. Based on cloud system performance and given wireless system attributes, the task dispatcher will make dispatch decisions to assign tasks to specific computational nodes. For example, as illustrated in Figure 5, virtual BS receivers generate the decoding tasks. Decoding task dispatcher will determine the specific decoding units for different decoding tasks. In our proposed OWSC, the decoding tasks can have the following wireless performance related attributes: TTL (Time to live), QoS (Quality of Service), SNR (Signal to Noise Ratio). Unlike the commonly accepted definition in Internet Protocol, in this case, TTL describes the timing constraint for decoding of the data packet. QoS describes the priority and the quality level of the data packet. SNR is achieved by channel estimation and will be used as input of the channel decoders. Based on these parameters, the dispatcher will select the most appropriate decoding unit. The task scheduler, system load balancing and controlling mechanisms of the conventional cloud computing should be modified to take into consideration wireless workload characteristics.

The proposed wireless cloud uses general purpose IT platforms. Linux, which is the de facto operating system, is not a real time OS. This will introduce jitter and uncertainty in processing time. Hardware-based timing modules and real time schedulers can be used to solve this problem.

3. Ongoing Efforts

Wireless networks should be simple to build and open. OWSC is proposed based on this premise. Unlike general purpose computing and Internet technologies, wireless technologies are standardized but have been highly proprietary. Only very big player can build real wireless network due to the cost.

For wireless-related research, open reference implementation of real wireless systems are difficult to find. Here the term “open” has two meaning, “open architecture” and “open access”. There are many research institutes and industrial communities working on the same goal. For example, the GNU Radio project aims to provide the signal processing runtime and processing blocks to implement software radios using readily-available, low-cost external RF hardware and commodity processors. At the end of 2008, Microsoft Research also released their Software Radio (Sora) project which is a novel software radio platform with fully programmability on commodity PC architectures. Sora combines the performance and fidelity of hardware SDR platforms with the programmability and flexibility of general-purpose processor (GPP) SDR platforms. However, the current approaches above are focusing on single GPP platform. In the beginning of 2010, our group released an open source project named OpenWireless. As illustrated in Figure 6, OpenWireless aims to provide cloud-based wireless computing framework and all key modules and interfaces for an open wireless communication systems on GPP platforms. The preparation for OWSC has attracted much interest in the past year.

Figure 6. Open wireless project

4. Conclusions

OWSC, an open cloud-based wireless radio access network is proposed as a platform and framework for the development and deployment of future wireless systems. Beyond better resource utilization, cost effectiveness and ease of management, it permits wireless virtual network operators to directly manage their own network though they own no infrastructure. Based on analysis of signal transmission, computation complexity as well as wireless system requirements, the proposed Open Wireless System Cloud is a promising architecture for future wireless communication system.

As described above, the advantages and main features of OWSC are as follows:

Open architecture and platform The architecture is based on general purpose open platforms. New wireless techniques can be easily developed and deployed on this platform.

Dynamic Management OWSC supports online monitor, analysis and automatic system resource balancing.

Virtualization Inherits from cloud computing, virtualization techniques such as Virtual BS, and virtual GW, which can help OWSC to further reduce cost.

Seamless coverage The collective processing of data from different antennas and areas enables OWSC to support true seamless coverage.

Scalability OWSC has incrementally expandable infrastructure, and support different workload combination and hardware configuration.

Efficiency OWSC makes optimal use of the shared resources of computation, interfaces and transmission. OWSC is much more efficient from a system perspective.

Flexibility OWSC can simultaneously handle the workload of different wireless standards and different service providers. OWSC can be composed of homogeneous open platforms and architectures.

Reliability OWSC is based on standard IT platforms which have been used in production environment for many years. The excellent operational reliability of very large cloud computing centers all over the world indicates OWSC will be similarly reliable.

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