Intel in
Communications

Implementing the IEEE* 802.16a Standard

The 802.16a standard specifies a metropolitan area networking protocol addressing frequency bands in the range between 2 GHz and 11 GHz. There are many factors that influence broadband wireless access system design, including implementations considerations in the PHY, MAC, scheduler, and radio, as well as propagation conditions in the communications channel which have an impact on link budget. This paper addresses the factors that are encountered in implementing the MAC, OFDM, PHY, and radio, and scheduler for a BWA system conforming to IEEE 802.16a.*

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The IEEE* 802.16a Standard

The IEEE* 802.16a standard, which specifies a metropolitan area networking protocol addressing frequency bands in the range between 2 GHz and 11 GHz, was released in January 2003 by the IEEE*. This new standard specifies a protocol that provides broadband connectivity without requiring a direct line of sight to close the link between subscriber terminals and the base station. In addition to providing wireless backhaul for 801.11 hotspots, it will enable a wireless alternative for cable, DSL, and T1 level services for last mile broadband access.

The initial 802.16 standard development project addressed LOS (line-of-sight) propagation environments in frequency bands between 10 GHz and 66 GHz. The 802.16a standard is designed for systems operating in bands between 2 GHz and 11GHz, where NLOS (non-LOS) environments predominate. To accommodate the link pathologies that characterize the NLOS environments, the 802.16a amendment to the standard required major changes to the PHY layer specification, as well as extensions to the MAC layer specification. Since the overwhelming majority of vendors will implement the OFDM PHY (based on a 256-point FFT), this paper is focused on implementation considerations for the MAC and the OFDM PHY.

PHY Layer

The OFDM signaling format was selected in preference to competing formats such as SC (Single-Carrier) and CDMA due to its superior NLOS performance,

which permits significant equalizer design simplification to support operation in multipath propagation environments.

Features of IEEE* 802.16a that are instrumental in giving this technology the power to deliver robust performance in a broad range of channel environments are adaptive burst profiles, forward error correction with concatenated Reed-Solomon and convolutional encoding (block turbo codes and convolutional turbo codes are optional), AAS (advanced antenna systems) to improve range/capacity, DFS (dynamic frequency selection)—which helps in minimizing interference, and STC (space-time coding) to enhance performance in fading environments through spatial diversity.

- **Advanced Antenna System.** By using more than one antenna element, AAS can improve range and system capacity by concentrating antenna radiation to individual subscribers.
- **Space Time Coding.** The IEEE* 802.16a MAC supports use of antenna diversity to combat fading. A specific implementation of STC, based on Alamouti’s original work, may be used on the downlink (DL) to provide space-time diversity.

- **Mesh Mode.** Mesh topologies improve coverage because traffic can be routed between individual Subscriber Stations (SSs) to circumvent obstructions and interference, in contrast to point-to-multipoint (star) topologies, where traffic only occurs between the BS (base station) and the SS.
- **Adaptive Modulation:** Adaptive modulation enables tradeoff between link robustness and capacity. Based upon current link conditions, a higher order modulation is used when the signal-to-noise ratio can support it. Modulation formats supported are QPSK, 16QAM, and 64 QAM. Adaptation is managed on a subscriber by subscriber, or a burst by burst basis.

MAC Layer

The MAC layer arbitrates access to the shared 802.16a medium, preventing simultaneous transmissions from separate Subscriber Stations. The MAC consists of three sub-layers. The Service Specific Convergence Sub-layer (SSCS) provides an interface to the upper layer entities through CS SAP (Service Access Point); it also provides a mapping of network data from the upper layer into MAC-SDUs that are sent to Common Part Sub-layer (CPS) via MAC-SAP. The MAC CPS provides the core MAC functions, including uplink scheduling, bandwidth request and grant, connection control, ARQ, and ranging. Privacy Sub-layer (PS) provides authentication and data encryption functions. The benefits of these features are summarized in Table 1.

Propagation Environment

There are many factors that influence broadband wireless signal propagation in frequency bands below 11 GHz. The typical propagation scenario is characterized by cells with service radius not exceeding 10 km, with terrain type and vegetation density varying widely depending on the geography of the cell location. Subscriber terminal antennas are usually mounted either on rooftops or under the eaves of buildings at heights varying between 2 and 10 meters, while basestation antennas are mounted on masts or rooftops at heights above the surrounding terrain ranging from 15 to 40 meters. These factors heavily influence the ability to close a communications link between the basestation and the subscribers in the service area. Economic success for a BWA deployment dictates a high cell coverage ratio, typically exceeding 90%.

Table 1 Key Features of the 802.16a MAC

Feature	Benefit
Connection-oriented	• Per connection QoS • Faster packet routing/forwarding
QoS support Continuous Grant Unsolicited Grant Real Time Variable Bit Rate Non Real Time Variable Bit Rate Best Effort	• Low latency for delay sensitive services (TDM Voice, VoIP) • Optimal transport for VBR traffic (e.g., video) • Data prioritization
ARQ	• Improves end-to-end performance
TDM/TDMA Scheduled UL/DL frames.	• Bandwidth efficiency
Power control	• Reduces interference
Adaptive Modulation Support	• Improves system capacity by enabling highest data rates permitted by channel conditions
Security and encryption (3–DES)	• Protects user privacy
Bandwidth on Demand	• Frame-by-frame capacity allocation

In addition to the mechanics of the installation, the wireless channel is further influenced and characterized by multipath delay spread, fading (due to intermittent obstructions and multipath interference), Doppler spread, and interference (consisting of co-channel interference emanating from adjacent cells or from other users in license exempt frequency bands, as well as adjacent-channel interference), and path loss, which is exponentially dependent on link distance, where the exponential factor is between 3 and 5. Since these propagation parameters are random variables that depend on terrain, foliage density, wind speed,, antenna beam width, and antenna height, knowledge of the channel is limited to a statistical characterization that is based on specification of the mean and variance of the channel parameters.

Delay Spread and Guard Interval

A key parameter that characterizes the received multipath signal energy that must be accommodated (either through equalization or excision) is the delay spread, which is the expressed as the standard deviation of the time variation of the received multipath energy [1]. The multipath energy is a result of scattering in the channel, and is characterized by a multipath delay profile, with rms delay spread of the entire delay profile following a log-normal distribution with a median that grows as a power of the link distance. Accordingly, for greater distances or more severe terrain, the PHY must accommodate greater values of rms delay spread. Table 2 provides typical rms delay-spread values corresponding to an omni antenna for the IEEE* 802.16a channel models [2]. The link distance (cell radius) for these delay-spread values is 7 k. It is important to highlight the range of rms delay spread, depending upon terrain conditions, shown as Terrain Type A, B, or C in the table.

Terrain Type A	The maximum path loss category; hilly terrain with moderate-to-heavy tree densities.
Terrain Type B	The intermediate path loss category.
Terrain Type C	The minimum path loss category; mostly flat terrain with light tree densities.

Table 2 IEEE 802.16a Channel Model Parameters

Channel Model	Terrain	Delay Spread rms (usec)
SUI-1	C	0.111
SUI-2	C	0.202
SUI-3	B	0.264
SUI-4	B	1.257
SUI-5	A	2.842
SUI-6	A	5.240

The mechanism designed into the IEEE 802.16a PHY to accommodate rms delay spread values that depend on the deployment scenario (cell size, scattering environment, terrain, etc.) is the guard period, Tg of the OFDM symbol, which is implemented by pre-pending a cyclic prefix [3], as depicted in Figure 1. The variability of the multipath delay spread with terrain and path distance is accommodated by a variable guard period, which for a given deployment scenario can be configured to a fraction of the period Tb taken from the set {Tg/Tb: 1/32, 1/16, 1/8, 1/4}.

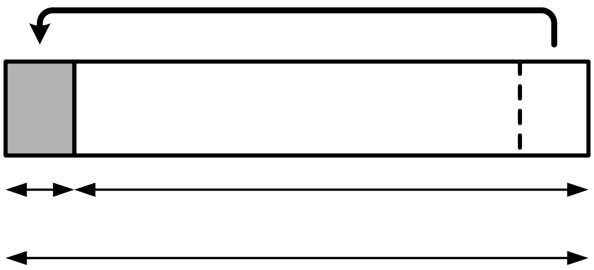

Figure 1 OFDM Symbol Structure

Link Design

Link Budget

Link budgets are based on modified Friis path loss equation for NLOS by adding the appropriate random variables to account for space-time variability and the extra attenuation due to obstacles of NLOS wireless channels.

Friis equation for LOS:

$$P_{rx} = P_{tx}\ G_t\ G_r\ 1/(4pi*f*d)^\wedge 2 \qquad (1)$$

Modified for NLOS:

$$SNR_r = P_{tx}+G_t+G_r-NF+A+Blog10(d)+Clog10(f)+f(H_{bs}) + g(H_{ss}) + R_s+R_k - (KT+10*log10(BW)+NF) \qquad (2)$$

Where:

- P_{tx} is typically in the range 20-35dBm,
- G is typically 0-20dB,
- B is typically 35-45dB and C>20,
- A an experimental value measured at some predetermined distance,
- $f(H_{bs})$, $g(H_{ss})$ are correction factors for BS and SS antenna height and depend on terrain etc.
- R_s is a random variable that models the effects of shadowing from larger objects and is modeled as a logN with sigma of 8-15dB (outdoor/indoor, environment)
- R_k is a random variable that models the variability of aggregate multipath energy at a small scale or over time and is modeled as a Rician distribution.

For extreme NLOS conditions this component (R_k) can generate +20dB of received signal variability and will typically require 0-15 dB of extra margin in the link budget [1]. Note from (2) that the R_X SNR changes dramatically across a typical NLOS cell over distance (d) and space-time (Rs and Rk). This equation is the basis for coverage analysis, and justifies the use of Link Adaptation (QAM, coding, TPC, subchannelization) and STC in modems implementing IEEE* 802.16a.

Coverage

Coverage is calculated form the link budget equation above. Since the R_X SNR is a random variable, for appropriate service in the target area, the SNR should be above the minimum demodulator sensitivity with the desired reliability (typically 99%-99.99%) and a large fraction of the population in the target coverage area (80%-95%) should be served. For these ranges an additional 10-15 dB margin to account for multipath fading and an additional 5-10 dB margin for shadowing (R_s) is typically added when computing the coverage region. Typical coverage areas for these BWA systems vary from 1 mile for the most pessimistic scenarios (lower power, lower antenna heights and gains, hilly environment) to over 25 miles for very benign propagation environments.

Space Time Coding (Alamouti)

Due to time-varying multipath the R_X aggregate energy can fluctuate very significantly in a T_X-R_X link with a single T_X antenna and a single R_X antenna. Incorporating more than one T_X antenna and/or R_X antenna enables the system designer to exploit the added information of this vector or matrix channel to ensure higher levels of reliability or to reduce the required coverage margin. The STC adopted by IEEE 802.16 is the Alamoui T_X diversity algorithm [4], which maps a single stream of data into two spatially separate antennas with a special 2-D complex mapping. This Space-Time T_X mapping and the appropriate MISO channel estimate at the T_X, achieves full 2^{nd} order diversity in the link, stabilizing the channel response and reducing the required fading margin by 5-10 dB depending on the environment.

Link Adaptation

The large variability of R_X SNR can be exploited by monitoring the R_X performance of both links and adjusting several of the d16 modem parameters to optimize the link reliability, maximize the user and system throughput and minimize the negative effects of interference to other users. The list of adaptable parameters includes power control, modulation order, code rate, and T_X BW (i.e. number of subchannels).

Transmit power control

TPC has three main system advantages. The first is to set the power to an adequate level that maintains a reliable link at the selected modulation order, coding rate and BW/subchannelization. The second is to minimize the negative effects of interference to neighbor cells using the same channels or adjacent channels. The last is to prevent the R_X power at the BS in a P2MP architecture from overloading the front end of the BS. The accuracy of TPC is more stringent for subchannelized OFDM so that multiple users sharing the OFDM symbol coexist without degradation, but this requirement is much more relaxed than the equivalent CDMA requirement.

Adaptive modulation

Denote by SNRr_min the minimum SNR required to demodulate the most robust IEEE 802.16 mode. Since BWA deployments must serve a large fraction of the population in the coverage area with high reliability, then SNRr(d,t)>SNRr_min for a very high fraction of users most of the time. The distribution of SNRr(d,t) depends heavily of the propagation environment, but typically the average of SNRr(d,t) will be 5 to 15dB higher than SNRr_min. This extra receiver SNR can be used to transmit reliably at modulations with higher order and lower coding overhead. By adjusting the modulation order (4QAM, 16QAM, 64QAM) and the coding rate of the concatenated RS-CC, the data throughput for each user can be maximized. Since this optimization depends on the specific channel characteristics, the variation of the channel should be tracked over time for continuing capacity optimization.

Typical Link Budget

A simplified DL link budget illustration is provided in Table 2. The typical BWA deployment modeled in this link budget uses 30m BS height and under-the-eve SS installation with active T_X STC to reduce the required multipath fading margin. The distances are computed to support 90% coverage and >99% reliability. Note that there is significant coverage variability depending on the propagation environment (e.g., hilly terrain, suburban environment, flat terrain, free space, etc.) It is particularly important to note that a free-space propagation assumption is in error by two orders of magnitude.

Table 3 Typical Link Budget

Parameters	Unit	Value
BS T_X power Into Antenna port		31
Number of T_X Antennas		2
T_X Antenna Gain, BS (90deg)	dBi	17
EIRP	dBm	51
R_X Antenna gain, SS (90deg)	dBi	16
Thermal noise/Hz	dBm/Hz	-174
R_X noise figure, SS (incl. cable loss)	dB	5
R_X noise density/ Hz	dBm	-169
Bandwidth (MHz)	MHz	3.5
R_X noise floor	dBm	-103.6
Shadowing Margin (sigma =8dB)	dB	5
Macro diversity gain	dB	2.0
S/N ratio(zero pathloss)	dB	171.2
Modem Setpoint (NLOS)	dB	6
Path loss margin	**dB**	**160.2**
Link Distance (Coverage area radius)		**km**
Erceg A	**km**	**5.0**
Erceg B	**km**	**7.7**
Erceg C	**km**	**10.5**
Cost 231 Hata	**km**	**4.3**
Free Space Model	**km**	**694.9**
Cost 231 WIM	**km**	**3.4**

MAC Implementation

Service Specific Convergence Sub-layer

802.16 MAC is designed to support point to multipoint broadband wireless access (BWA) applications, providing both real-time (e.g. voice, video) and non-real-time services over broadband connections to the customer premise. Figure 2 shows a SSCS can be connected to upper layer entities via Ethernet or TDM interfaces to provide voice / data convergence services. An important feature of BWA is to insure the needs of applications with different QoS requirements, including bandwidth, latency, delay variation, packet loss rate, burst size, can be satisfied.

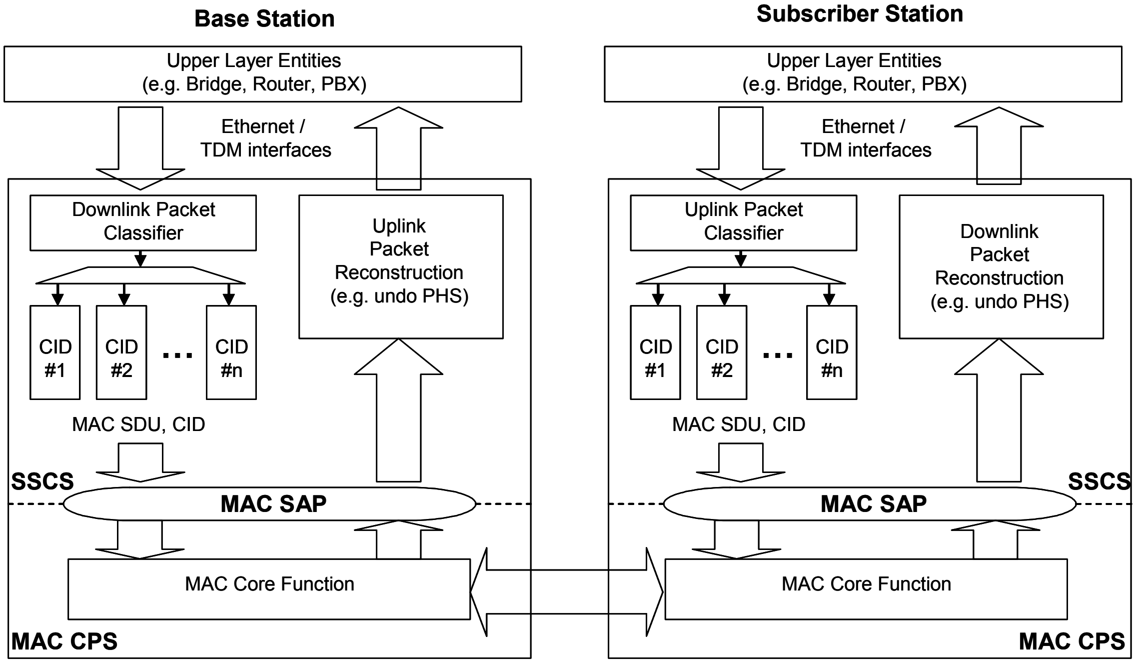

Figure 2 Wireless Classification and CID Mapping

A service flow is a MAC layer transport service, providing unidirectional transport of packets either uplink or downlink, and is characterized by a set of QoS parameters. Packet classifier in SSCS is designed to map a connection from an application to a service flow based on a set of matching criteria, including QoS parameters or destination address. Currently, SSCS supports ATM encapsulation and packet encapsulation. QoS mechanism for ATM is defined in “Traffic Management Specification” [5]. Packet CS supports various QoS protocols, for example Diffserv (Differenced Services) and 802.1P. In addition, SSCS supports packet header suppression; a repetitive portion of the payload headers of the higher layer is suppressed by the sending entity and restored by the receiving entity to improve bandwidth utilization efficiency. Packet Reconstruction reassemblies the packets arriving at the peer before presenting them to upper layer entities.

MAC-CPS exports the following primitives at MAC-SAP enabling SSCS to create and tear-down connections between SS and BS for service flows and exchange MAC-SDU between SSCS and CPS.

- *MAC_CREATE_CONNECTION*
- *MAC_CHANGE_CONNECTION*
- *MAC_TERMINATE_CONNECTION*
- *MAC_DATA*

Each connection is identified by CID (Connection Identifier) and is associated with a set of QoS parameters. For example, when a matching is found in the packet classifier, a service flow is mapped to a CID. SSCS then passes the MAC SDU and CID to MAC CPS by calling MAC_DATA.request primitive.

MAC Common Part Sub-layer

Scheduling services

The downlink traffic, transported from BS to SS, is based on point-to-multipoint architecture, which BS broadcasts data packets to all SSs. The uplink bandwidth is shared between SSs based on TDMA (Time Division Multiple Access) architecture, where uplink scheduling services are designed to improve the efficiency of bandwidth request/grant process while meeting the QoS needs for each SS. 802.16 defines the following scheduling services:

- **Unsolicited Grant Services (UGS):** UGS is designed to support constant bit rate (CBR) or CBR like SFs, such as T1/E1 emulation, VoIP without silence suppression. UGS SF is created by specifying Unsolicited Grant Size, Nominal Grant Interval, Tolerated Grant Jitter, and Request/ Transmission Policy.
- **Real-Time Polling Services (rtPS):** rtPS is designed to support real-time SF that generate variable size data packets on a periodic basis, such as MPEG video.
- **Non-Real-Time Polling Services (nrtPS):** nrtPS is designed to support non-real-time SF that require variable size data grant burst type on a regular basis, such as FTP
- **Best Effort Services (BE):** Best effort services are typically provided by the Internet today for web surfing.

When the SSCS calls the MAC_CREATE_CONNECTION.request primitive to create a new connection, the "scheduling service type" parameter specifies the type of scheduling service for such connection.

Bandwidth request / grant mechanism

IEEE 02.16 defines the following mechanisms for SS to request bandwidth for uplink traffic. These mechanisms are also used to support scheduling services listed above.

- **Implicit requests**: Implicit request is used in UGS. The SF parameters are negotiated at connection setup, and no message exchange is required during data packet transport.

- **Bandwidth request messages**: SS can use either a stand-alone "Bandwidth Request" header or "Piggyback Request" (incremental or aggregate) in the Grant Management subheader of MAC PDU to convey the bandwidth request to BS.

- **Bandwidth grant messages**: For an SS, the bandwidth requests are addressed to the individual connections, while the bandwidth grants are addressed to the SS's Basic CIDs. SS may re-distribute bandwidth among its connections, maintaining

QoS and SLA. There are two types of bandwidth grant messages – Request IE and Data Grant Burst Types IE. Request IE provides an opportunity for SSs to send bandwidth requests, and can be broadcast, multicast, or unicast to an SS's Basic CID. Data Grant Burst Types IE is always sent in unicast mode, and can be used for sending bandwidth request or payload data.

- **Polling**: *Unicast*–An SS is polled individually via UL-MAP slot. It can be used in rtPS and nrtPS. *Multicast and Broadcast*–Contention based bandwidth request used when insufficient bandwidth is available to individually poll many inactive SSs. It is used in rtPS, nrtPS, and BE. *Poll-me bit*–PM bit in Grant Management subheader is used by SS to request bandwidth for non-UGS services

IEEE* 802.16a designs DL-MAP and UL-MAP messages to control the allocation of downlink and uplink bandwidth to SSs. The OFDM frame structure depicted in Figure 3 provides an example to show how uplink bandwidth request / grant mechanisms and downlink packets distribution work. Figure 3 is based on Frequency Division Duplexing (FDD) where the uplink and downlink traffic operate on separate channels. OFDM PHY supports the frame-based transmission.

A downlink frame starts with a preamble, which is used for PHY synchronization. The preamble is followed by a FCH (Frame Control Header) that contains DL-MAP and UL-MAP. FCH may also contain short MAC control messages, such as DCD (Downlink Channel Descriptor) and UCD (Uplink Channel Descriptor) that define the characteristics of downlink and uplink physical channels. A DL-MAP consists of multiple DL_MAP_IEs. Each DL_MAP_IE contains StartPS and DIUC (Downlink Interval Usage Code) parameters. A downlink frame is divided into an integer number of Physical Slots (PSs) that is 4 modulation symbols long. StartPS indicates the start of downlink MAC-PDU burst in units of PS, where the first PS in a given frame has StartPS = 0. IEEE 802.16a uses adaptive burst profile to define the transmission parameters, such as modulations and FEC coding that can be dynamically assigned to SSs on a burst by burst basis according to link conditions. DIUC and UIUC (Uplink Interval Usage Code) parameters identify the burst profile for downlink and uplink respectively. Downlink / uplink burst profiles and their association with DIUC and UIUC are defined in DCD and UCD messages. Since DL-MAP only provides the burst profile and location of data packets in a frame, each SS needs to receive and decode every data packet to determine whether a packet belongs to him or not based on CID in the MAC header.

The UL-MAP contains the Allocation Start Time and the DL_MAP_IEs. The Allocation Start Time defines the effective start time of uplink allocation in units of minislots. The size of minislots is specified as a number of PS's, and is carried in the UCD message. The Allocation Start Time is referenced from the start of the downlink frame, and may start in the current frame or next frame. Allocation Start Time is followed by Initial Maintenance IE that is broadcast to all SSs, and therefore, is a contention based bandwidth request. BS sends Initial Maintenance IE to enable new SS joining the network. So, it uses initial ranging CID = 0 and initial ranging UUIC = 1. Initial Maintenance IE should start from the Allocation Start Time with the length indicated by the Duration parameter in units of OFDM symbols. BS sends Request IE enable SS to request uplink bandwidth. As shown in Figure 3, the Request IE can be sent in broadcast mode or unicast mode to SS by using broadcast CID or unicast CID accordingly. Data Grant Burst Type IEs provide opportunities for SSs to transmit one or more MAC – PDUs. Data Grant Burst Type IE contains UIUC indicating the burst profile to use and CID indicating which SS has the right to send the uplink burst. UL-MAP ends with the end of map IE that has Duration 0.

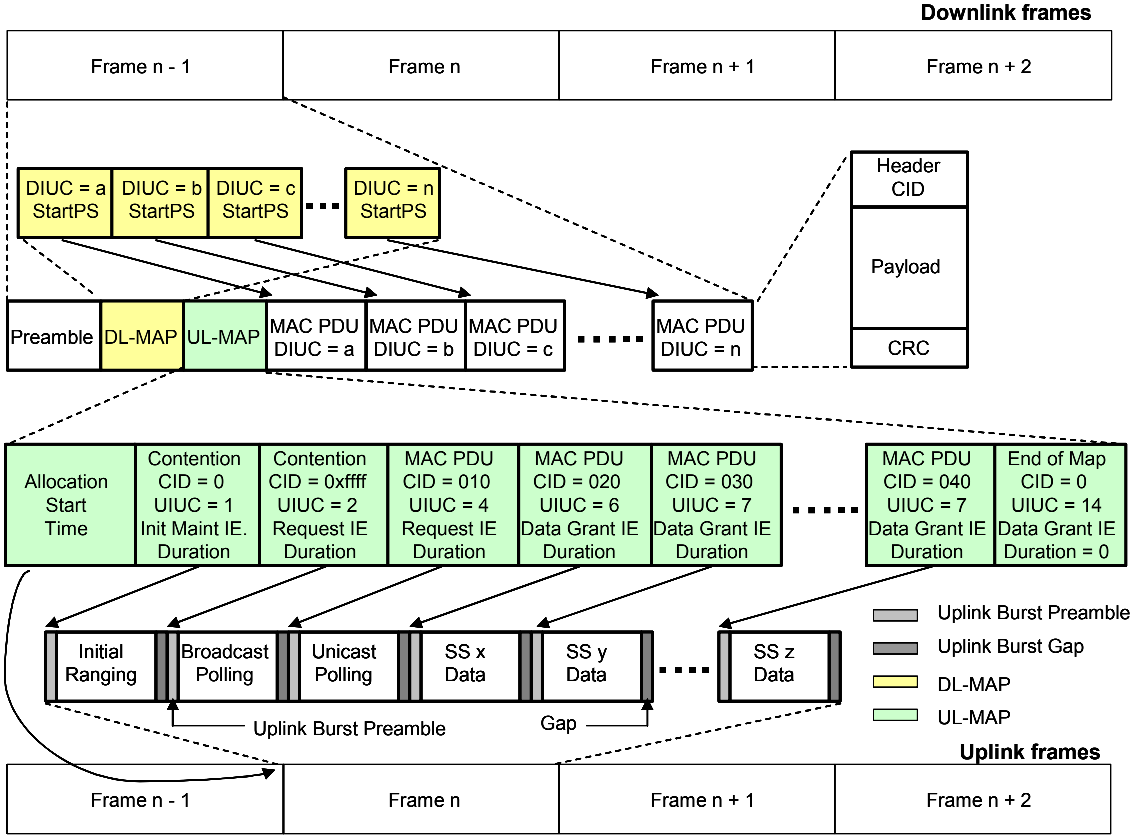

Figure 3 Typical OFDM Frame Structure (FDD)

Ranging

Ranging is a process of adjusting the transmitter timing advance of SSs such that uplink bursts arriving at BS are aligned to the required minislot boundary. There are two types of ranging procedures – initial ranging and periodic ranging. Initial ranging is carried out when a new SS tries to access the network, and therefore is normally executed during the SS initialization. Periodic ranging is for SSs to continuously monitor and make adjustment if necessary on a periodic basis to insure correct transmit timing. The following procedure describes the Ranging process.

a) SS acquires and synchronizes to a downlink channel.

b) SS obtains DL-MAP, UL-MAP, DCD, and UCD parameters, which describe downlink / uplink transmission characteristics, from a downlink frame.

c) SS initiates Ranging process by sending a RNG-REQ message with CID = 0 on an Initial Maintenance interval found from UL-MAP.

d) If BS is not able to decode RNG-REQ message properly, it should send a RNG-RSP with CID = 0, frame number, initial ranging opportunity number, RF power level adjustment, offset frequency adjustment, timing offset correction parameters.

e) SS recognizes RNG-RSP message based on frame number and initial ranging opportunity number, and makes adjustments on T_X power level and frequency / timing offset.

f) SS sends another RNG-REQ message in contention mode with CID = 0 on the next opportunity.

g) Once BS successfully receives the RNG_REQ message, it shall allocate Basic and Primary Management CIDs, and add the Basic CID to the polling list.

h) BS returns a RNG-RSP message addressed to individual SS (SS's MAC address) with Basic and Primary Management CIDs.

i) SS recognizes RNG-RSP message based on its own MAC address. SS stores Basic/Primary CIDS received from RNG-RSP message, and makes local parameters adjustment if necessary.

j) For periodic ranging, BS sends a UL-MAP with station maintenance IE to SS using SS's Basic CID.

k) SS replies to station maintenance opportunity with RNG-REQ message to start periodic ranging process for T_X power and frequency / timing adjustments.

Automatic Repeat Request

IEEE* 802.16a optionally supports ARQ (Automatic repeat request), an error-control mechanism in which a request for re-transmission is generated by the receiver when an error in transmission is detected. ARQ reduces the delay that higher layer might observe due to data loss. For example, if an SDU was received in error and dropped at the air interface without ARQ, the higher layer would have to request a retransmission end-to-end, thus incurring more delay than if the SDU was retransmitted at the air interface.

ARQ in IEEE* 802.16a is designed to work with fragmentation. The transmitting MAC entity fragments and SDU into smaller pieces and numbers them in order before sending them to the PHY interface. The transmitter entity maintains a window of fragments that were transmitted but not acknowledged. If the window is full before an ACK is received then transmission stalls. Other wise the transmitter keeps updating the boundaries of the window based on the fragments sent and the ACKs received. Figure 4 shows the ARQ state machine.

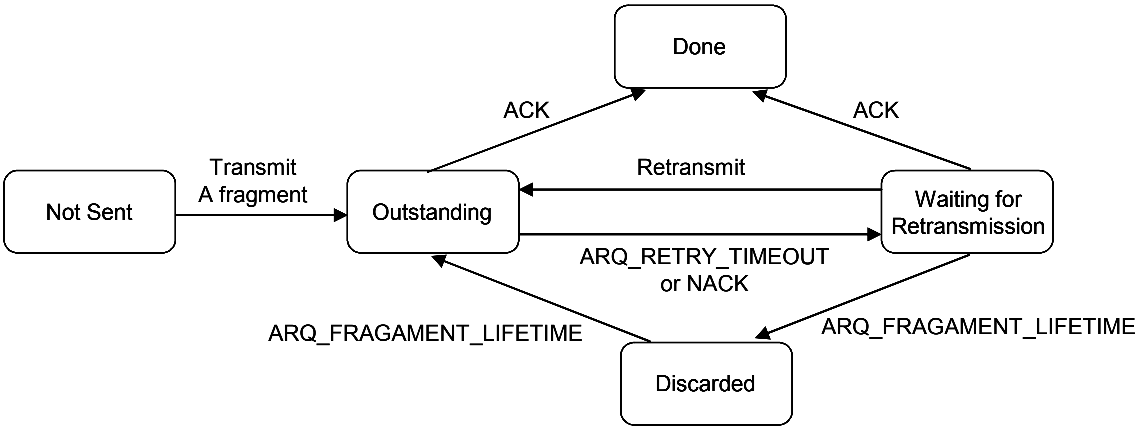

Figure 4 ARQ State Machine

The receiver MAC entity maintains a similar window. The boundaries of the window are marked by the last received sequence number the last acknowledged fragment. The 802.16a™ MAC supports 3 different ACKs: a cumulative ACK, a selective ACK, and combination of both cumulative and selective. In the cumulative mode the ACKs indicate the successful reception of all fragments up to the fragment sequence number imbedded in the ACK. In selective mode, the ACK carries more information about what particular fragments were not received correctly.

Scheduler

IEEE* 802.16a does not specify a particular scheduler algorithm. The standard defines all the messages and mechanisms that are necessary to convey allocations and BW requests. This opens up the field between different providers to differentiate their systems by providing more advanced scheduling mechanisms that meets a specific application while at the same time being interoperable.

In an IEEE* 802.16a compliant system a scheduler is required to compute complex allocation maps to service the user population. In the OFDM subchannelization mode the scheduler should schedule users across time and frequency adding another dimension to the problem. Link quality, fragmentation, and QoS parameters should also be considered when PDUs are scheduled.

The basestation is required to support many CIDs simultaneously. However, not all CIDs are active. For the sake of efficiency, the scheduler can keep an active list of CIDs that have data to transmit in the current frame or have pending data to be sent. The CIDs are added/removed from the activity list based upon certain rules. For example, assume that the CID is inactive to start (queue length = 0). When the queue length becomes > 0 the queue becomes active and is added to the corresponding activity list. The CID is serviced in order and is removed from the activity list when the queue length becomes 0.

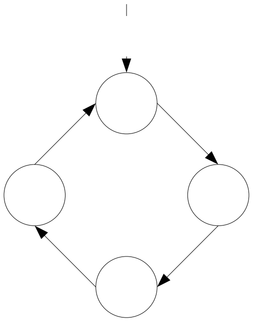

Figure 5 Activity lists

Active lists can also be organized in multiple scheduling layers. These scheduling layers can correspond to priority or different QoS parameters layers. Figure 6 depicts such an implementation.

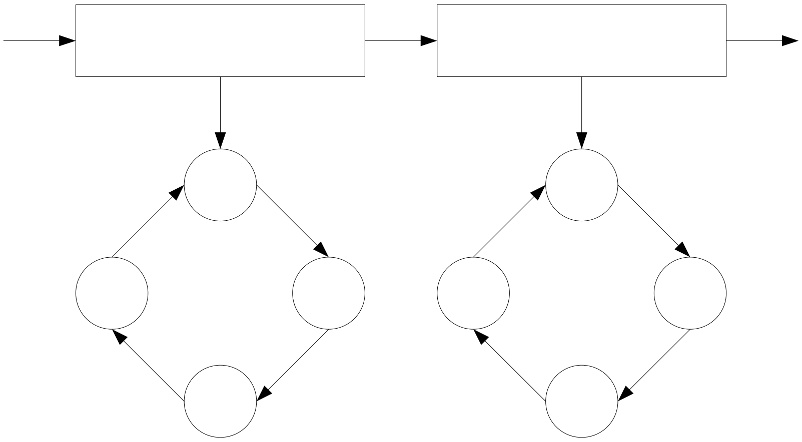

Figure 6 Layered Scheduling

MAC Architectures

Typical MAC architectures to implement these functions and services encompass the high level abstraction of MAC functions as specified in IEEE* 802.16a are depicted in

Figure 7 and

Figure 8. The actual implementation may vary, as some optimization may be necessary to meet certain timing constraints.

Subscriber Station MAC Architecture

Figure 7 depicts the SS MAC architecture. The SSCS Downlink Packet Classifier and Uplink Packet Reassembly functions are addressed in the MAC Implementation discussion. The CPS is comprised of the following functional components.

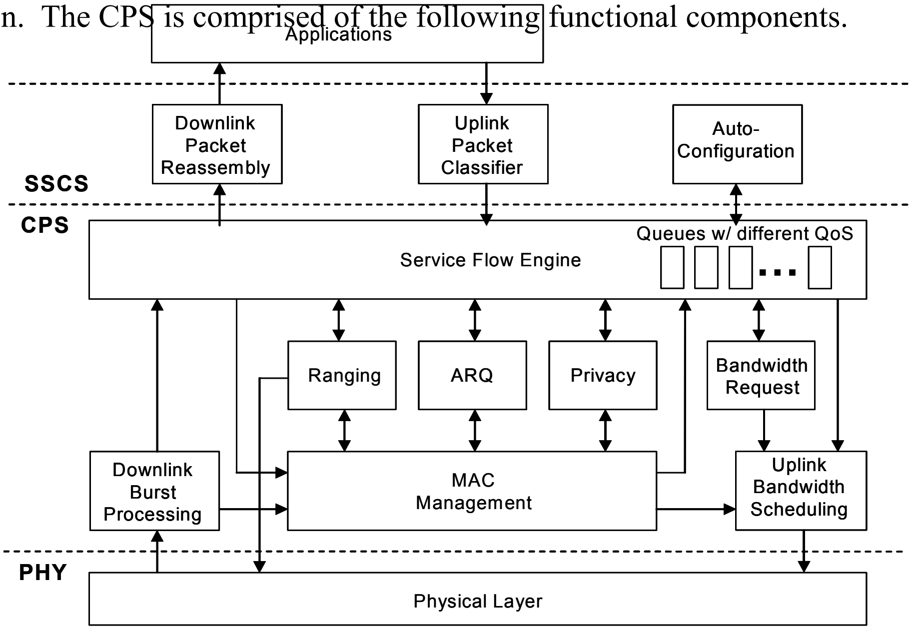

Figure 7 SS MAC Architecture

a) MAC Management (MACM). IEEE* 802.16a defines a set of MAC Management Messages to control the operation of the MAC CPS sub-layer. MACM is responsible for processing MAC Management messages received from the Downlink Burst Processing. MACM may distribute messages to other components to complete the management task. If MACM must send a response to BS, it will forward the message to the Service Flow Engine, so it can be sent on the proper CID.

b) Downlink Burst Processing (DBP). DBP extracts data bursts from the downlink frames based on the DL-MAP. DBP monitors each MAC-PDU to determine whether the given SS is the receiver of such burst based on whether the CID in the MAC header matches one of the CIDs being assigned to the given SS. DBP then forwards MAC Management messages to MACM, and CS messages to the Service Flow Engine.

c) Uplink Bandwidth Scheduling (UBS). UBS is responsible for transmitting an uplink burst to the BS based on the UL-MAP. UBS receives a MAC-PDU or BW Request message from SFE and Bandwidth Request (BR) respectively. UBS also receives the UL-MAP from MACM to assist bandwidth scheduling.

d) Bandwidth Request (BR). BR creates a Bandwidth Request Header message based on the CID, amount of bandwidth, and incremental / aggregate parameters from SFE. The Bandwidth Request Header message is sent to UBS for transmission to the BS.

e) Privacy (PRV). PRV implements authorization and privacy key management functions based on PKM-REQ and PKM-RSP messages. PRV passes encryption keys to SFE if encryption is implemented in software or to hardware modules if encryption is implemented in hardware.

f) Automatic Repeat Request (ARQ). ARQ implements the Automatic Repeat Request function based on ARQ-Feedback, ARQ-Discard, and ARQ-Reset messages. It sends ACK or NACK messages to SFE for retransmission if necessary.

g) Ranging (RNG). RNG implements ranging functions based on RNG-REQ and RNG-RSP messages. It interfaces to hardware via a MAC device driver to adjust RF power level and frequency/timing offset. Upon completion of the ranging process, RNG sends Basic and Primary Management CIDs to SFE.

h) Service Flow Engine (SFE). SFE controls the service flows to provide MAC transport services across the BWA radio network to applications. It contains multiple queues associated with different QoS parameters to meet the needs of various applications. SFE should ask BR to request uplink scheduling services for supporting QoS requirements. BS provides uplink bandwidth grant on a per SS basis, so SFE should arbitrate which application has access to the uplink bandwidth. IEEE 802.16 defines a set of MAC messages (e.g. DSA-REQ, DSA-RSP, DSD-REQ DSD-RSP, DSC-REQ, and DSC-RSP) to enable SFE to create, delete, or change service flows.

i) Auto-Configuration (A-CFG). An important goal of A-CFG is to avoid, as much as possible, an end-user involvement or truck roll in SS set-up and configuration. An SP can enter the information of a subscriber and requested services (e.g. bandwidth, QoS, subscriber ID, etc.) into the network server ahead of time, A-CFG can autonomously download these configuration parameters upon creation of a management service flow. This enables a subscriber to start the service without SP's intervention.

Base Station MAC Architecture

Figure 8 shows the BS MAC Architecture. The similarity between SS MAC and BS MAC architectures is due to the fact that they are peers across the BWA radio network. A major difference is that downlink traffic from BS is broadcast to SSs, so bandwidth request/grant is no longer necessary in BS MAC. However, several new components specific to the BS MAC are required.

a) Scheduler (SCHD). SCHD is responsible for creating the DL-MAP, which defines the destination of each data burst in a downlink frame, as well as the UL-MAP that dictates which SS has the right to send the uplink burst. SCHD creates the map based on a set of criteria, such as QoS parameters, bandwidth request, and link conditions (burst profiles).
b) Connection Admission Control (CAC). Since bandwidth on the wireless media is quite limited, CAC is a differentiating feature to insure each new service flow created will not cause any service degradation of existing service flows. CAC controls the number of service flows in a cell by taking into account the traffic descriptor of service flows. CAC also provides long-term performance statistics.
c) Configuration Management (CM). CM is the depository of service flow configuration data that SP's Network Management System has entered. A-CFG in the SS can autonomously retrieve this data upon creation of the management service flow.
d) Link Management (LM). LM implements ranging functions, and interface to hardware to adjust RF power level.

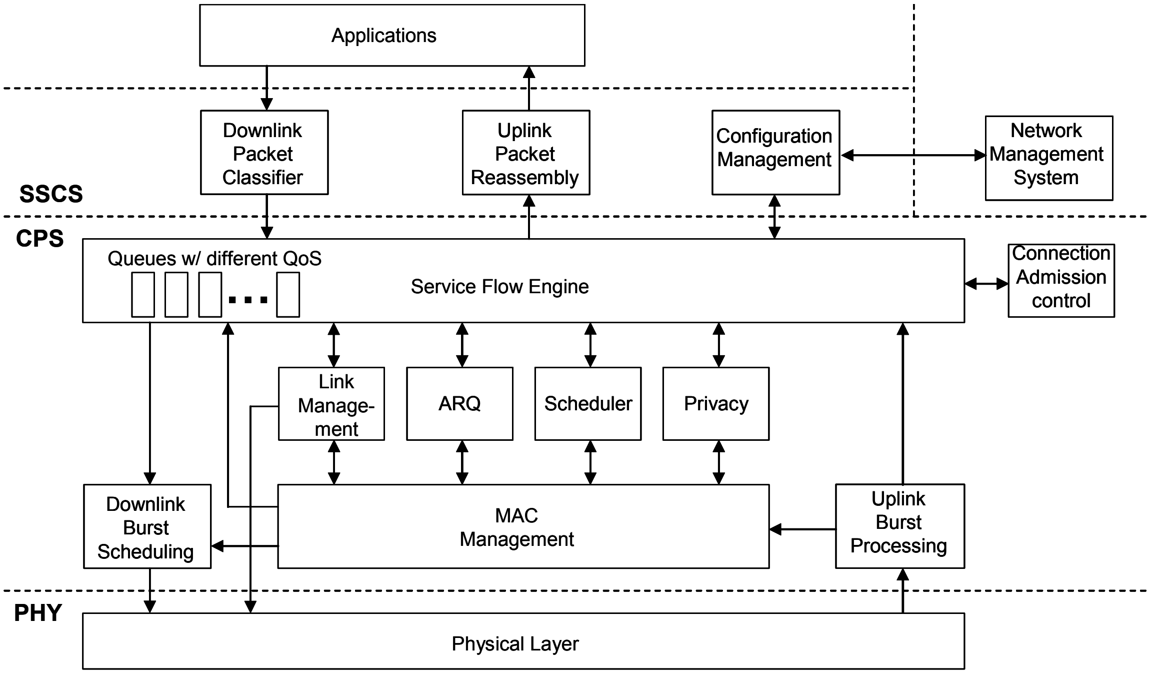

Figure 8 BS MAC Architecture

Radio Interface Design

I/Q Baseband Interface

A typical Zero-IF sampling architecture is depicted in Figure 9 and Figure 10. In the Zero-IF sampling architecture, the I/Q complex components are used to reconstruct the signal. The primary advantages of zero-IF are (1) lower-power radios are possible since power is not required to support high IF s and (2) lower cost results from reduced external component count. The disadvantages of zero IF are (1) the design of the radio is made complicated by Self LO mixing products which add interference into the baseband signal, (2) flicker noise of devices degrade the signal at baseband, and (3) since most of the filtering is done at the end of the R_X chain, interfering components must be supported all the way through the R_X chain, and (4) the I and Q components must be controlled to match the gain, phase and DC offset to minimize SNR degradation inside the bandwidth of interest.

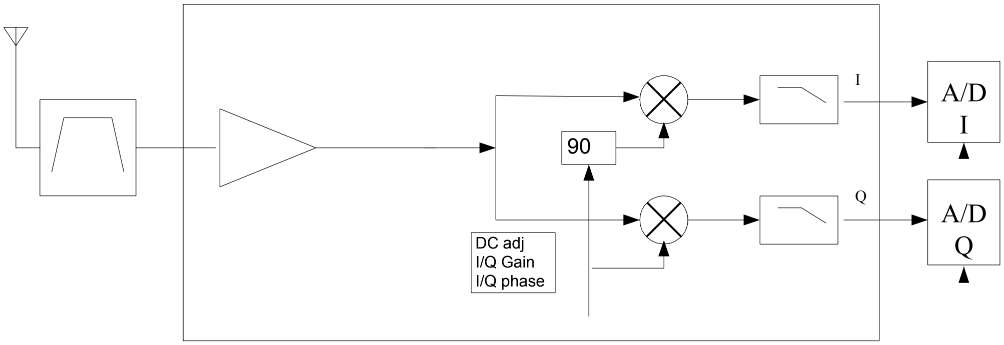

Figure 9 Zero IF Sampling Receiver Architecture

Typical values for I/Q gain mismatch in RFIC devices are 0.2dB and 1 deg for phase mismatch. Narrow sub-carrier spacing between OFDM tones (2 kHz) with these values can result in SNR s of -36.8 dB for 64 QAM. In addition, calibration is required, consisting of digital correction of I/Q impairments introduced by the RFIC and the signal data converters. For the T_X side a sideband power level measurement can be made, but the accuracy of the power measurement determines the effectiveness of the calibration. Appropriate I/Q compensation is then implemented in the digital domain. For the R_X side a known good constellation of the OFDM signal is received, which allows I/Q compensation to remove the gain and phase mismatches.

Since IEEE 802.16a specifies optional bandwidths of 1.25, 1.75, 2, 3, 5, 7 and 10 MHz, the cutoff for the final low pass filters in the zero IF radio (which provide adjacent/alternate channel rejection) must be adjustable to accommodate these bandwidths. The filters must address the most aggressive requirement, which is the requirement for the most sensitive modulation/coding format. The ACI rejection requirement specified in IEEE 802.16a is 4 dB for 64-QAM rate-2/3; alternate channel rejection for this modulation/coding format is 23dB.

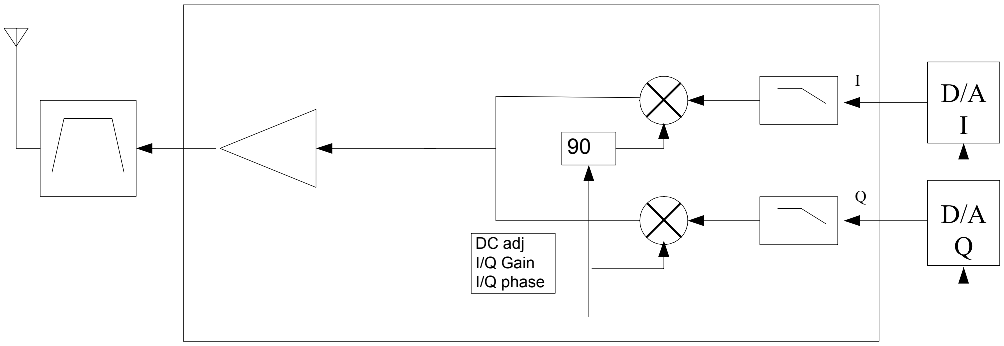

Figure 10 Zero IF Sampling Transmitter Architecture

IF Interface

A typical super-heterodyne architecture for IF sampling, using two IF stages, is depicted in Figure 11 and Figure 12. This design reduces complexity by spreading the gain and filtering over the two IF stages. High performance RFICs can be built, but at a higher cost, and using multiple IF stages also increases the power dissipation of the

RFIC. An added complexity results from having two stages of frequency conversion which demands careful frequency planning of the IF frequencies to avoid spurious mixing frequency products falling into the band of the desired signal. The transmitter requires a SAW filter to provide the required degree of LO and image rejection. The receiver requires a SAW filter to meet adjacent/alternate channel rejection requirements. In addition, a 2^{nd} SAW or a bandpass filter may be required for spurious filtering. An AA (anti-aliasing) filter is required to limit the bandwidth at the A/D input to conform to the Nyquist sampling criterion. A distinct advantage of the IF-sampled solution is that the gain/phase mismatch associated with I/Q has been eliminated. In addition, a single A/D and D/A s is required, as opposed to two for the Zero-IF architecture.

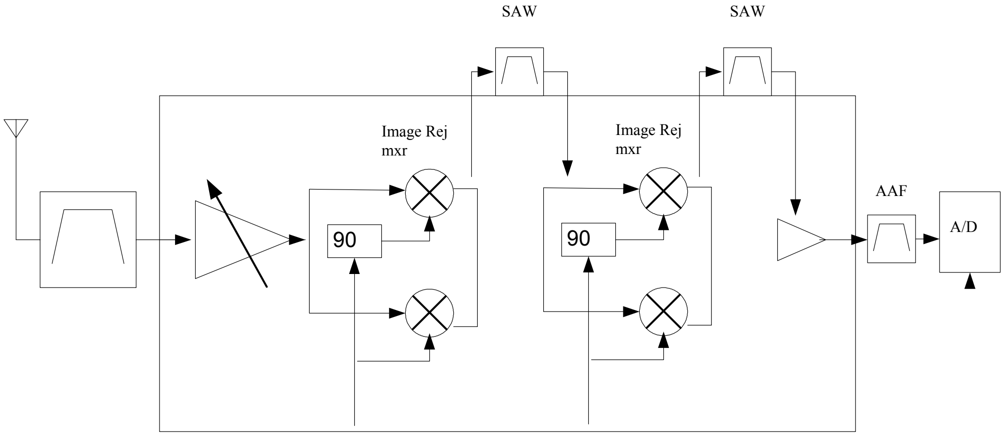

Figure 11 IF Sampling Receiver Architecture

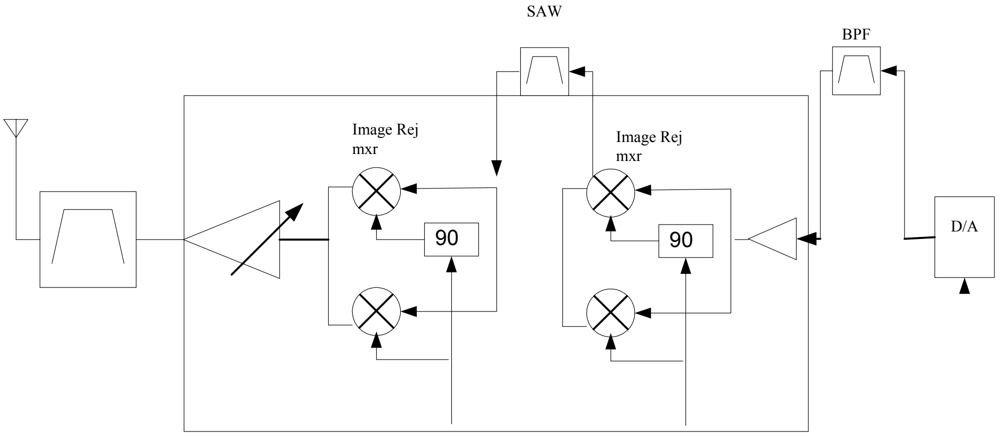

Figure 12 IF Sampling Transmitter Architecture

Frequency planning to select the IF frequency for T_X and IF frequency for R_X is complicated by the fact that SAWS are typically custom devices and are not readily available for all bandwidths over all frequencies. The frequency planning phase of the design usually includes cataloguing the frequencies of available SAW filters. The wide range of channel bandwidths specified in IEEE 802.16a is expected to promote development of wide SAWS that can accommodate as many channels as possible. The tradeoff will be between the A/D and digital filtering, using as few SAWS as possible to cover the various frequency/bandwidth requirements. Calibration of the R_X RFIC is not required, since digital sampling is conducted at the IF frequency. The only calibration required on the T_X side is that of the power level. IEEE* 802.16a also requires that 1 dB +/- 0.5 dB steps must be provided over a 50 dB (+/-3 dB) range. In addition, regulations in the licensed bands may place requirements on absolute power, which in turn will impose T_X calibration requirements.

AGC

Typical R_X RFICs can have 70-80 dB of AGC covering a voltage range of 0 to 3V. Sufficient filtering of AGC inputs into the RFIC must be ensured to avoid reducing the SNR of the signal. An analog AGC is usually implemented to allow a continuous change in the signal level without disrupting the phase. On the T_X side, a digital stepped attenuator can be implemented which changes the gain only when the signal is not being transmitted. The digital attenuator simplifies the IEEE* 802.16a requirement to provide T_X power adjustments in 1 dB increments.

RF Filtering

The primary RF bands addressed by IEEE* 802.16a are 2.4 GHz (ISM), 2.5-2.7 GHz (MMDS), 3.4-3.8 GHz (ETSI), and 5.1-5.9 GHz (ISM/UNII). Front-end RF filters do need to be changed to accommodate these different frequency bands. In HD-FDD (Half-Duplex Frequency Division Duplex) systems, filtering requirements are less demanding than for their full-duplex FDD cousin, because the T_X will not degrade the R_X since it is turned off while in R_X mode. Similar reasoning shows that the same filters can be used for TDD (Time-Division Duplex) systems.

Conclusion

The IEEE* 802.16a standard provides an excellent "last mile" alternative to cable and DSL due to its inherent flexibility in dealing with harsh propagation environments and communications link pathologies. Its high throughput, scalability, and QoS features, combined with techniques for coverage extension, provide an unparalleled third pipe to reach broadband subscribers worldwide.

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