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Abstract	Proposal for 802.16 to use Netro's CellMAC media access control protocol
Purpose	
Notice	
Release	
IEEE Patent Policy	

Proposal to Use CellMAC™ as MAC Layer for BWA

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Introduction

Netro's ATM/TDMA/FDD air interface, CellMAC which has been under development since 1995, was purpose-built to enable wireless operators to provide voice and broadband data and multimedia services to the small and medium enterprise. Netro's AirStar broadband wireless access system, with the CellMAC™ air interface fully developed, has been commercially shipping for over a year. AirStar, which is also available as Lucent's OnDemand Broadband Wireless Access system and as Siemens' SRAMP, with CellMAC™ is installed in over 30 customer sites worldwide at multiple frequencies many of which are in commercial operation delivering voice and broadband data services to the small and medium enterprise.

Netro believes that CellMAC is the only air interface that is commercially available today at multiple frequencies that satisfies all of the System Requirements set forth by the 802.16. With the IEEE 802.16 moving at a rapid pace, Netro is pleased to open CellMAC to this standards activity and requests that it be given full consideration.

Overview

A wireless ATM point to multipoint network imposes unique requirements to the medium Access Control (MAC) layer. The MAC layer must provide a regulating mechanism for sharing the common bandwidth among the multiple users, and in addition comply with additional requirements that are arising because of the commercial success of wireless ATM access networks, such as:

- Service Transparency - Any service, T1/E1 (structured and unstructured), POTS, Internet Protocol, Bridged Services, Frame Relay, or Cell Relay can easily be mapped onto ATM adaptation layer and service class with commercially available chipsets.
- Future proof architecture - Any current or future service can be easily mapped onto ATM.
- Dynamic Bandwidth Allocation - The ability to achieve statistical multiplexing for bursty data services, which allows bandwidth and equipment reuse by a substantial factor.
- Core network independence - Base station can easily adapt traffic for transport on any core network, TDM, ATM, or IP.
- Grade of Service - Bandwidth allocation is in accordance with the PCR, SCR, CDV, and MBS traffic contract for each service.
- Scalability - All real-time processing can be purely hardware based enabling scalability up to 155 Mbps and beyond through scaling clock frequency of ASIC silicon.
- PMD Layer independence - Operates at arbitrary bit rates to enable use on any channelization plan worldwide. Can support either FDD or TDD operation.
- High spectral efficiency and low overhead - Spectral efficiency equivalent to point to point systems. Mini-slot and piggy-back mechanism in upstream enable low MAC overhead and symmetry of spectral efficiency.

The CellMAC reference model is shown in Figure 1. The physical medium dependent (PMD) sublayer employs 4 and 16QAM modulation in a frequency duplex mode and is the subject of a separate contribution. The transmission convergence sublayer abstracts the media access control layer from the PMD layer and maps the link management, bandwidth management, and user data transfer mechanism onto the PMD layer.

The Media Access control layer has three main components: link management, bandwidth management, and user data transfer. The link management function provides for automatic subscriber transmit power control and ranging calibration, and for the admission of new users onto the network. The bandwidth management function processes bandwidth reservation requests from subscribers and schedules constant-bit-rate and bursty data traffic according to quality of service criteria. The user data transfer provides the data link control for mapping higher layer user data onto TC-PDUs and for user data encryption over the air interface.

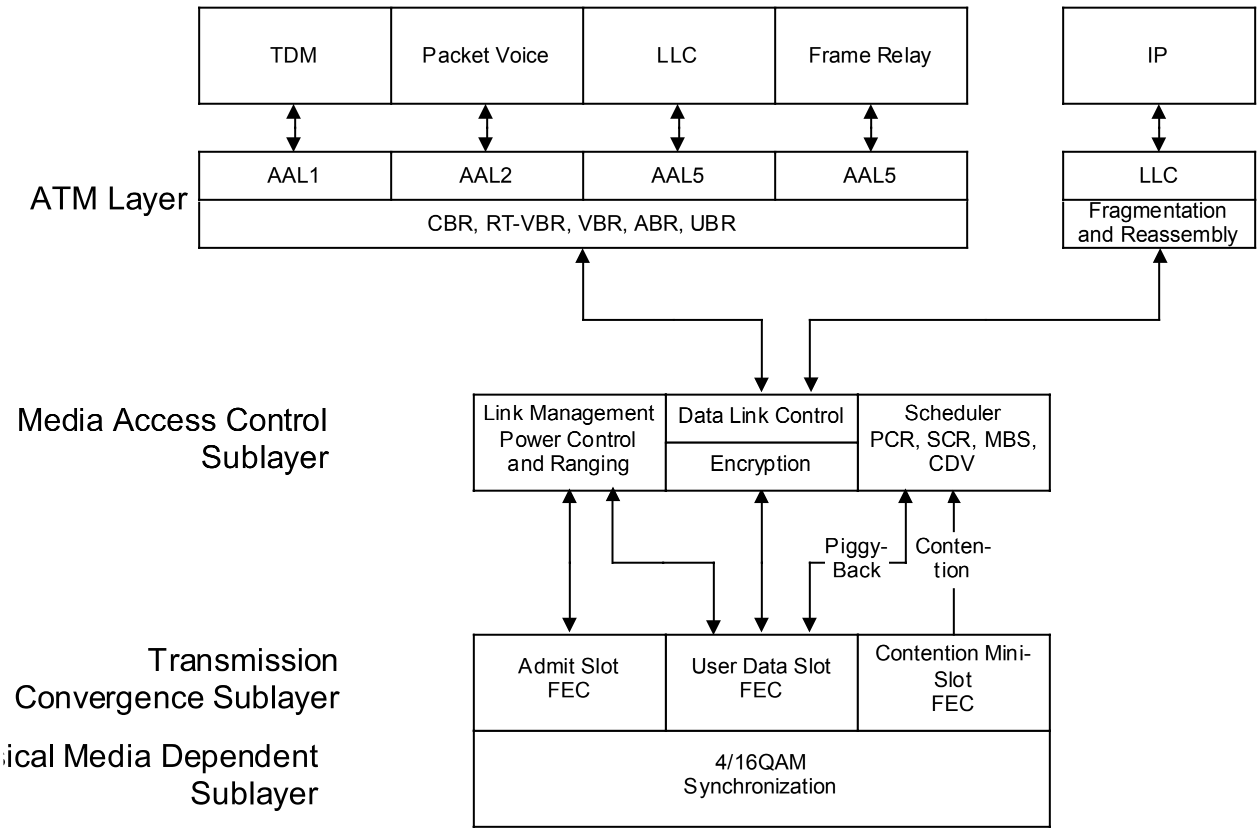

Figure 1: CellMAC™ Reference Model

Transmission Convergence Layer Overview

The transmission convergence layer abstracts the Media Access Control Layer from the Physical Medium Dependent Sublayer. The transmission convergence sublayer maps the Media Access Control mechanisms for link management, bandwidth reservation and granting, and user data transfer onto the physical medium dependent sublayer. The TC layer described herein is specified for operation with physical medium dependent sublayer which employs frequency division duplexing and 4/16QAM modulation[1]. This TC layer can be extended to support time division duplexed PMD layers and different modulation schemes such as 8PSK, 32/64QAM, or OFDM.

The transmission convergence layer achieves symmetric spectral efficiency between the upstream and downstream transmissions. Both employ 67 octet protocol data units. Each protocol data unit carries a net user payload of 47 bytes. This achieves a spectral efficiency which is in accordance with ETSI TM4 recommendations of four E1s per 7 MHz channel, or 8xE1 per 14 MHz channel.

The downstream direction is time division multiplexed and operates in a broadcast mode with a distinct MAC address for each subscriber terminal. Although time division multiplexed, there is no concept of a frame structure where time slots are mapped to subscriber terminals. Rather, traffic is passed downstream as it is received from the network interface in an on-demand fashion.

The transmission is divided to timeslots, each timeslot carries a 67-byte TC-PDU including one ATM cell.

The upstream direction consists of bursts from any of the terminals, each burst contains a TC-PDU that includes an ATM cell and/or MAC-level signaling, as discussed below.

The upstream mode is time division multiple access (TDMA), but no TDM frame exists in this direction either.

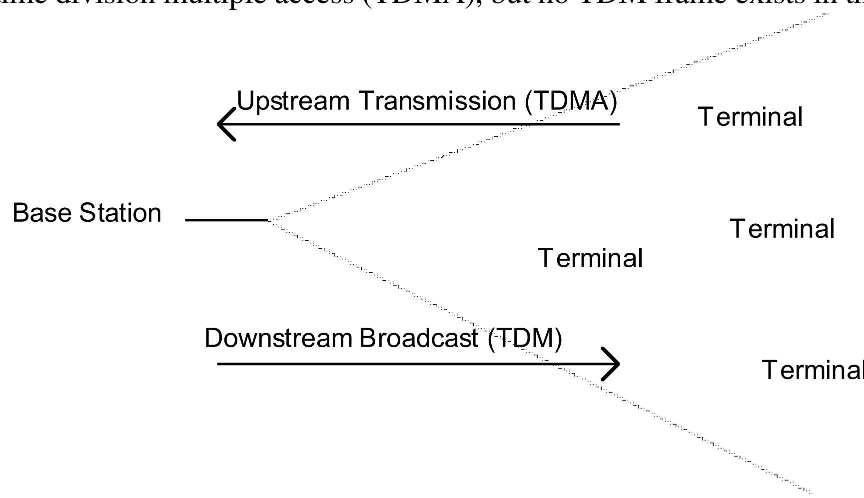

Figure 2: Downstream Broadcast/ Upstream Bursts

Downstream

The 67 octet downstream TC-PDU consists of 48 octets of user payload, 9 octets of FEC, and 9 octets of CellMAC overhead.

67 Octet Downstream PDU		
CellMAC Header (9)	Payload (48)	FEC (9)

Figure 3: Downstream TC-PDU

The PDU ends with a 9-bytes FEC field, of which 70 bits contain BCH code with t=7. The details of the FEC and scrambling parameters are given in a separate PHY contribution [1].

The MAC header includes the following MAC-related information:

- Subscriber Terminal Identifier (STI) -Destination terminal MAC address of this TC-PDU.
- Connection Identifier (CID) of this TC-PDU. The Connection Identifier is mapped to the VCI for ATM transport. For IP transport, a single value for the CID used for pure connection-less transport, or the CID can be used in association with differentiated services.
- STI/CID of a grant to transmit one burst in the upstream direction (usually different from the destination of the downstream TC-PDU).
- Grant-type: this indicates whether the next upstream transmission is for a user data transfer, a contention slot, or new user admission burst.
- Response field, providing feedback to a previous upstream burst transmission, indicating burst power and timing adjustments, and/or collision indication, based on the type of the previous burst.
- Payload Type Indicator. For ATM transport systems this is mapped to the ATM payload type indicator field.
- Cell Loss Priority, For ATM transport system this is mapped to the ATM cell loss priority field.
- Header Error Check

Of special significance in the above format:

Each downstream PDU carries one grant, thus each upstream burst is individually controlled by this grant. This enables a variety of framed or unframed traffic scheduling algorithms to be implemented.

Each grant specifies the Connection Identifier which allows the base station to control the upstream flow of each and every service from each and every subscriber terminal on a per connection basis. In ATM transport systems, this is a critical requirement for maintaining ATM QoS and fairness in bandwidth allocation across all subscribers and services delivered from each subscriber.

Upstream

The upstream flow includes bursts of user data traffic, contention slots and admission bursts.

Upstream User Data TC-PDU

67 Octet PDU			
PMD Overhead (3)	CellMAC Header (9)	Payload (48)	FEC (8)

Figure 4: Upstream User Data TC-PDU

This is the PDU that carries user data and management traffic. This PDU is the same size as the downstream PDU: 67 octets. However, since it is a burst, 3 bytes of PMD header are required for burst synchronization.

The eight octets for FEC consists of a 54-bit BCH code with a correction factor of t=6, and two bits reserved.

The CellMAC Header includes the following information:

- Subscriber Terminal Identifier (STI) - Source terminal CellMAC address of this User Data TC-PDU.
- Connection Identifier (CID) of this TC-PDU. For ATM transport systems, the CID would map directly to the VCI of the ATM cell. For IP transport systems, the CID can be mapped to a VLAN ID per IEEE 802.11Q, to a logical IP interface, or not used for connection-less transport.
- A bandwidth reservation request including CID and Cell Count of any connection within this terminal, requesting COUNT=0 to 7 TC-PDUs).
- A second CID and Cell Count, same as above, for another (or same) connection.
- Payload Type Indicator. For ATM transport systems this is mapped to the ATM payload type indicator field.
- Cell Loss Priority, For ATM transport system this is mapped to the ATM cell loss priority field.
- Header Error Check for integrity checking of the CellMAC Header.

Note that with this header, each terminal can send two independent bandwidth reservations, including up to 7 TC-PDUs each, thus every user data transmission is an opportunity to request up to 14 more TC-PDUs without resorting to a contention slot, to be described next.

Upstream Contention Slot

A terminal that did not transmit for a long time, probably because it had no traffic, has no opportunity to piggyback a request as discussed above. Such terminal may use a contention slot to send a grant request.

11 Octet Contention Minislot TC-PDU		
PMD Header (2)	Request (5.5)	FEC (3.5)

Figure 5: Contention Minislot TC-PDU (one of 6)

A contention slot is a 67-octet slot divided into six 11-octet minislots and one extra 1-octet gap. Each minislot includes:

- Subscriber Terminal Identifier (STI) - Source terminal CellMAC address of the request.
- Reservation Request consisting of the CID and Cell Count of any connection within this terminal, requesting Count=0 to 7 TC-PDUs).
- A second reservation request consisting of CID and Count, for another (or the same) connection within the subscriber terminal.

Note that a minislot request carries the same two requests as an upstream User Data TC-PDU. Any of the six minislots may come from a different terminal.

Since this is a contention slot, more than one terminal may transmit in the same slot. If this happens, a collision is reported and the terminals try again, using a back-off algorithm.

A ternary valued feedback for each contention minislot is provided in the Response Field of the downstream CellMAC header. The two-bit response field for each contention minislot is encoded to give an indication of successful transmission, collision, or nothing received. The use of ternary valued feedback from the base station to the subscriber enables the most advanced of random back-off algorithms to maximize throughput on the contention minislots.

Upstream Admit Slot

A new terminal must register itself by transmitting a special packet called “Admit request”. An Admit slot is a granted slot period in which new terminals can transmit a 32-octet structure, that is preceded by guard slots in which no grants are given, because a new terminal does not have a precise delay information to compensate for the distance to the base station. The key information in an Admit Request is the terminal’s IEEE 48-bit MAC address that identifies the device uniquely. In response, the terminals receive a downstream packet with an assigned CellMAC address (STI) and delay/power setting.

32 Octet Admit PDU				
PMD Header (8)	IEEE MAC (6)	STI (1.5)	Reserved (9.5)	FEC (8)

Figure 6: Upstream Admit TC-PDU

The upstream Admit TC-PDU has the following structure:

- 8 octet sync preamble
- 6 octet IEEE MAC Address
- 1.5 octets STI
- 9.5 octets reserved
- 54 bits FEC (BCH t=6)
- 2 bit reserved

Traffic Scheduling

Because each downstream TC-PDU carries in the MAC Header a grant for the next upstream transmission, a variety a traffic scheduling algorithms may be implemented based on the service objectives of the equipment vendor. It is not the intention of this contribution to recommend a specific scheduling algorithm for standardization, but to leave this up to each vendor as a means for differentiation without sacrificing interoperability.

Operational Overview

Downstream Scheduling

The flow in the downstream direction, being a broadcast of all traffic from the base station into the aggregate bandwidth of a sector, is not different from a wireline port egress scheduler typical in ATM switches or IP routers. The downstream direction can be managed by commercially available ATM traffic management chipsets or with simple FCFS queuing for IP based systems. Because of the simplicity of this transmission direction, it is not further discussed.

Upstream Scheduling

The upstream transmission scheduling direction is unique and challenging. The general principle is now apparent from the CellMAC description so far:

- Requests per connection arrive at the base station from the MAC overhead of the user data transmission and from contention minislots. Periodically the base station will
- The reservation requests are processed by the scheduling algorithm and corresponding grants are queued.
- For CBR services, the base station can schedule the traffic directly without requiring reservation requests from the subscriber terminals by self generating grants and inserting them into the grant queue.
- The base station generates one grant per upstream slot, and transmits this grant in the downstream CellMAC header.
- The grant specifies which terminal (STI) and which CID within that terminal will transmit.
- The grant recipient transmits one user data TC-PDU in the upstream.
- The timing of transmission of the upstream TC-PDU is in the same order of arrival of the corresponding grants.

Since there is one to one mapping between a grant and a transmission of an ATM cell, the grants scheduler effectively manages from the base station the queue of all the user data on all connections within each of the terminals. This relationship is crucial for understanding the advantages of centralized scheduling.

Reservation Request Efficiency

CellMAC was purpose-built to meet the needs of wireless operators delivering voice and broadband data and multimedia services to the small and medium enterprise. Implicit in this is that the operator will be delivering voice and data services simultaneously. The piggy-back reservation request mechanism was developed with concept that a CBR connection for voice services could also be used as a control plane communications link for reservation requests. This concept is unique to CellMAC. The result of this is that when a user has a voice service, all of their reservation requests for data services can be piggy backed onto their connections for voice so that the subscriber would never need to use contention-based access.

In addition, reservation requests can also be piggy-backed onto data transmissions, not just voice transmissions. Hence, during a large file transfer, after the first contention-based reservation request, all further reservation requests can be piggy-backed onto the user data transmissions. Hence, only a single reservation request can be required during an FTP or HTTP session.

Even in the worst case of short data packets where a CBR connection is not present, CellMAC's contention-based reservation request mechanism is as bandwidth efficient as any other MAC protocol for any other physical media. Since there are 6 minislots, and since each minislot may carry up to 14 TC-PDU requests, the yield of a slot is up to 33.726 TC-PDUs. Even without the piggyback mechanism, the contention slots can allow utilization of 97%, making CellMAC as efficient for contention based reservation requests as any other MAC protocol.

In systems operating in the field, CellMAC typically requires less than 5% of the upstream bandwidth to be allocated to contention-based reservation requests. CellMAC can easily operate at 1% of the upstream bandwidth allocated for contention-based reservation requests for typical Internet traffic patterns. As a result of such a low percentage of the upstream bandwidth needing to be utilized for contention-based access, CellMAC achieves truly symmetrical spectral efficiency for user data.

Overview of Netro's Traffic Scheduler

While it is not the intention of this contribution to recommend standardization of the scheduling algorithms, an overview of Netro's scheduling implentation is described to provide validation of that the reservation request mechanism can meet the most difficult of QoS demands, that of carrier-grade ATM networks. Having proven its capability to handle these most difficult requirements, CellMAC's ability to support the traffic management requirements of pure IP based systems should be evident.

Netro's patented scheduling algorithms are implemented in ASICs which are in their second generation. A hardware-based approach enables the MAC processing to scale linearly with the ASIC clock speed enabling it to support channel bit rates up to 155 Mbps and beyond.

Link Management

The link management function implements the subscriber transmit power control and ranging calibration. This is used for two purposes: managing admission of new users into the network, and ongoing power and timing calibration of users.

New User Admission into Network

When the base station is provisioned with a new user, it begins to periodically allocate admit slots in the upstream for the new user to admit. The admit slots are contention-based, so the new users implement a random back-off algorithm based on collision-feedback from the base station.

The admit TC-PDU contains a globally unique IEEE MAC address for the subscriber terminal. If the IEEE MAC address of the subscriber terminal matches that which has been provisioned through the network management system into the base station, then the base station allows the user to admit and assigns it a Subscriber Terminal Identifier after completion of the transmit power and ranging calibration.

With the 32 octet admit TC-PDU in a 67 octet time slot, there are 35 octets of guard time which can allow ranging resolution of up to 3.5 km for a 7 MHz channel. For faster channel bit rates, or larger cell sizes, additional 67 octet guard slots can be allocated.

Subscriber Transmit Power Control and Ranging

Using the same mechanism as for new user admission, every subscriber terminal receives instantaneous power and timing corrections from the base station as a result of each user data TC-PDU transmitted by the subscriber.

Encryption

DES encryption on the air interface is employed on the 48 byte payload of the downstream TC-PDU and upstream user data TC-PDU. The CellMAC header, and the FEC fields are not encrypted. Likewise, contention minislot and admit slot TC-PDUs are not encrypted. Each STI has a unique DES key. Encryption is performed on the air interface segment only for privacy of each subscriber terminals transmissions. End to end encryption is outside the scope of the air interface MAC layer specification, and will typically be performed by customer owned VPN equipment. The mechanism for key distribution is outside the scope of the MAC layer specification.

Data Link Control

The DLC ensures direct mapping of ATM traffic onto TC-PDUs, and can also support native IP transport systems using VLANs, or tag-switching. The ATM cell header fields for VCI, PTI, and CLP are mapped directly into their equivalents in the CellMAC header. The TC-PDU payload size was fixed at 48 octets to support ATM cell payloads.

The VPI field in the ATM cell header is replaced and extended with the Subscriber Terminal Identifier field in the TC-PDU. Since the Base Station in ATM networks will function primarily as an access multiplexer, all subscriber terminals will effectively share a common ATM UNI on the network interface of the base station. Hence, providing each subscriber terminal with its own ATM UNI is unnecessary. For most services, only VCCs need be supported. However, for native ATM services to the customer premise, VPCs might also need to be supported. To support VPCs, a subscriber terminal can be configured with multiple STIs.

Statement of Compliance to MAC Call for Contributions

Adherence to System Requirements

Unlike other MAC protocols which were developed for cable applications, unlicensed wireless bands, or residential wireless applications, CellMAC was purpose-built to enable wireless operators to deliver voice and broadband data services to the SME and multi-tenant unit. Netro's AirStar system, employing the CellMAC air interface, is delivering T1/E1 based services, Nx64kbps services, IP, Bridged servies, and Frame Relay. CellMAC natively supports ATM cell relay services.

Bounds to Delay

Measurements on Netro's AirStar system demonstrate less than 20 ms two way round trip delay for CBR services, with as low as one DS0 per VCC. Roundtrip delay is typically less than 8 ms for T1/E1 based CBR services. Netro's experience with its wireless operator cu-stomers is that the roundtrip delay is low enough that they do not have to use echo cancellation when negotiating their interconnect agreements with incumbent local exchange carriers.

Payload and Bandwidth Efficiency

CellMAC achieves the recommendations of the ETSI TM4 committee on spectral efficiency for TDMA systems of 4xE1 per 7 MHz channel. CellMAC's highly efficient reservation request scheme consisting of piggy-back and contention-based minislots enables it to achieve symmetric spectral efficiency between the upstream and downstream channels. Because each reservation request and each grant carries the connection identifier, CellMAC enables traffic scheduling algorithms which can maintain QoS for each service within each subscriber terminal.

Simplicity of Implementation

CellMAC lends itself to an all hardware implementation. On the base station, Netro has implemented the TC and MAC layers in a two chip using a state machine architecture which can support two air interface channels. On the subscriber, the TC and MAC functions are in a single ASIC. Netro believes this makes for a simpler and lower cost implementation than competing MAC protocols typically require embedded RISC processors with tight requirements real-time processing firmware to implement the traffic scheduling algorithms.

Netro's AirStar system, along with Lucent's OnDemand Broadband Wireless Access system and Siemens' SRAMP, each employing CellMAC, has been deployed at multiple frequencies in over thirty networks worldwide, some of which for over a year. In the same time competing MAC protocols are still in the technical trial phase or just coming to market, is a testimonial to its simplicity in implementation.

Scalability

Because CellMAC lends itself to a state-machine driven hardware implementation, it can scale in channel capacity by merely scaling the clock frequency on the ASIC silicon. Competing solutions which require software or embedded RISC based real-time processing of the MAC are finding and will continue to find it difficult to scale in channel capacity.

Service Support Flexibility

By natively supporting an ATM link layer, CellMAC guarantees support for any current or future service. AirStar today, using CellMAC, supports T1/E1, fractional T1/E1, IP, Bridged services, and frame relay.

Robustness

As CellMAC was required to support an ATM link layer, it requires a physical medium which can achieve cell loss ratios equivalent to a wireline network, 10^{-6} or better. This is consistent with all fast packet protocols which implement retransmission request end to end, and not on each segment of the network. The base station reports successful transmission of each contention-based reservation request, and there are time-outs for reservation requests that were successfully transmitted, but for which no grants were received.

Security

CellMAC provides for DES encryption of the 48 byte payloads for user traffic with a unique DES key per subscriber terminal.

Physical Channel Configurability

CellMAC controls the allocation of slots types, user data, contention minislot, or admit slot, in the upstream direction.

Maturity

Netro began development on AirStar in 1995. Netro's AirStar system utilizing the CellMAC air interface has been in trials with customers since 1997, and began commercially shipping during Q4 1998. AirStar, along with Lucent's OnDemand Broadband Wireless Access system and as Siemens' SRAMP, has been deployed in over 30 operator networks at multiple frequencies, of which many are in commercial operation generating service revenue. Netro's AirStar system is currently delivering unstructured T1/E1, fractional T1/E1, IP, bridged services, and frame relay services, giving it the largest range of service support of any point to multipoint system.

Convergence with Existing Technologies

While CellMAC was purpose-built specifically to meet the needs of wireless operators delivering voice and broadband data services, it leveraging technologies and algorithms from elsewhere in the datacom and wireless industry. The CellMAC subscriber ASIC interfaces directly with commercially available PMD layer ASICs from the cable modem or terrestrial video broadcast industries. The FEC is based on well-known BCH codes. The traffic scheduling algorithms are derived from ATM traffic management ASICs.

Other MAC protocols which were not purpose-built for broadband wireless access applications will require numerous extensions to meet the needs of wireless operators delivering voice and broadband data services to the SME and MTUs. As a result, today's commercially available ASICs for those MAC protocols will not meet the needs of broadband wireless operators.

Independence of Physical Media

While CellMAC, in its present form, operates with both 4 and 16QAM modulation with frequency-division duplexing, it can operate with a variety of PMD sublayers with the appropriate TC layer specification. CellMAC already supports arbitrary channelizations and both 4 and 16QAM modulation. With the appropriate TC layer specification, CellMAC can support other QAM constellations including 8 PSK, or 32 or 64QAM, or OFDM physical layers. Also the time delay between the grant transmission and upstream slot is configurable which can allow it to operate in half-duplex mode in a time-division-duplexed PMD layer. Netro believes that this makes CellMAC the MAC protocol with the most flexibility in supporting a variety of PMD layers.

[1] Netro Contribution for CellMAC 4/16QAM physical layer to 802.16 Physical Layer Task Group