The 5-UP™ Protocol for Unified Multiservice Wireless Networks

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ABSTRACT

Popular wireless networking protocols such as Bluetooth, IEEE 802.11, and HomeRF were originally developed for the 2.4 GHz frequency band by organizations that made design tradeoffs based on values such as complexity, price, and performance. Because the protocols were developed independently and these values differed according to the markets and applications the organizations intended to serve, the various protocols do not easily interoperate with one another and can cause significant mutual interference when functioning in the same radio space. The problem becomes especially acute in environments such as residential networks where a single network may be required to serve a broad range of application classes.

A newer high-performance wireless LAN standard, IEEE 802.11a, operates in the 5 GHz band and offers much higher speeds than previous WLAN standards, but does not adequately provide for unified networks that support multiple classes of devices with differing speed, performance, power, complexity, and cost requirements. These differing classes of devices will become increasingly important as LANs move beyond the limits of office-oriented computer interconnection services and into the realm of data, video, and audio distribution services for interconnected devices in offices and homes. The 5 GHz Unified Protocol (5-UP™) is a proposed extension to existing 5 GHz wireless LAN (WLAN) standards that supports data transfer rates to over 54 Mb/s and also allows a wide variety of lower-power lower-speed devices carrying diverse traffic types to coexist and interoperate within the same unified wireless network.

INTRODUCTION

The proliferation of cheaper, smaller, and more powerful notebook computers and other mobile computing terminals has fueled tremendous growth in the WLAN industry in recent years. WLANs in business applications enable mobile computing devices to communicate with one another and access information sources on a continuous basis without being tethered to network cables. Other types of business devices such as telephones, bar code readers, and printers are also being untethered by WLANs.

Demand for wireless networks in the home is also growing as multicomputer homes look for ways to communicate among computers and share resources such as files, printers, and broadband Internet connections. Consumer-oriented electronics devices such as games, phones, and appliances are being added to home WLANs, stretching the notion of the LAN as primarily a means of connecting computers. These multiservice home networks support a broad variety of media and computing devices as part of a single network. A multiservice home network is depicted in Fig. 1.

Analysts project that the number of networked nodes in homes, including both PC-oriented and entertainment-oriented devices, will top 70 million by the year 2004 (Parks Associates, *Networks in the Home: Analysis and Forecasts*).

As can be inferred from Fig. 1, the multiservice home network must accommodate a variety of types of traffic. The ideal multiservice home LAN:

- Supports differing traffic types such as low- and high-rate bursty asynchronous data transfer, telemetry information, multicast streaming audio and video, and interactive voice
- Provides sufficient bandwidth to support an increasing amount of high-rate traffic both within the home and transiting the gateway
- Allows multiple types of devices to operate on the network without interfering with one another
- Efficiently supports diverse devices with differing price, power, and data rate targets
- Efficiently allocates spectrum and bandwidth among the various networked devices
- Can economically provide a single gateway through which services can be provisioned and devices can communicate outside the home
- Provides coverage throughout the home, preferably with a single access point

Popular wireless networking protocols such as Bluetooth, IEEE 802.11, and HomeRF meet some, but not all of the multiservice home networking requirements. Furthermore, because the protocols

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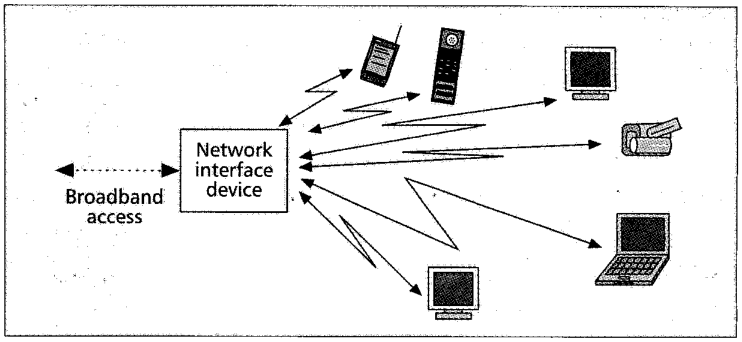
were developed independently, they do not easily interoperate with one another and can cause significant mutual interference when functioning in the same radio space. The 802.11a WLAN standard [1–3] offers speed and robustness for home networking that previous WLAN standards have not offered. Although access to this bandwidth for home networking is relatively recent, cost-effective chipsets have already been announced, such as Atheros' AR5000 802.11a Chipset including an all-CMOS Radio-on-a-Chip (ROC). However, devices such as cordless telephones, PDAs, and networked appliances do not require all of the speed and features that 802.11a offers. An extension to these protocols that allows less expensive, lower-power, lower-data-rate radios to interoperate with higher-speed, more complex 802.11a radios is presented in this article. The goal of this extension is to maintain high overall efficiency while allowing scalability: the ability to create dedicated radios with the capabilities and price points appropriate to each application and traffic type.



■ **Figure 1.** *A multiservice wireless home network with broadband access.*

BACKGROUND: 802.11 PHY LAYER

Wireless networking systems can be best understood by considering the physical (PHY) layer and media access control (MAC) layers separately. The physical layer of 802.11a is based on orthogonal frequency-division multiplexing (OFDM) [4], a modulation technique that uses multiple carriers to mitigate the effects of multipath. OFDM distributes the data over a large number of carriers that are spaced apart at precise frequencies.

802.11a provides for OFDM with 52 carriers in a 20 MHz bandwidth: 48 carry data; 4 are pilot signals (Fig. 2). Each carrier is ~300 kHz wide, giving raw data rates from 125 kb/s to 1.5 Mb/s per carrier depending on the modulation type — binary phase shift keying (BPSK), quadrature PSK (QPSK), 16-quadrature amplitude modulation (QAM), or 64-QAM — employed and the amount of error-correcting code overhead (1/2 or 3/4 rate). Note that the different data rates are all generated by using all 48 data carriers (and 4 pilots).

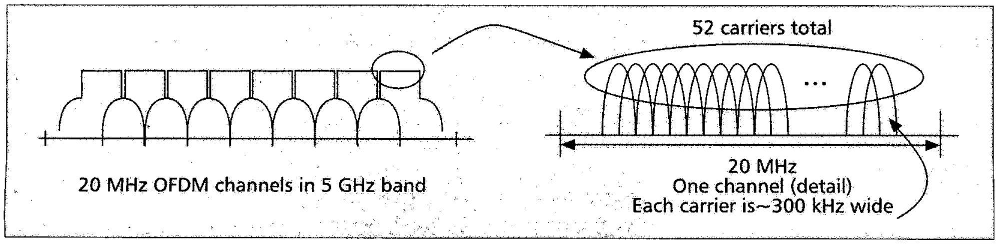
OFDM is one of the most spectrally efficient data transmission techniques available. This means that it can transmit a very large amount of data in a given frequency bandwidth. Instead of separating each of the 52 subcarriers with a guard band, OFDM overlaps them. If done incorrectly, this could lead to an effect known as intercarrier interference (ICI), where the data from one subcarrier cannot be distinguished unambiguously from its adjacent subcarriers. OFDM avoids this problem by making sure that the subcarriers are orthogonal to each other by precisely controlling their relative frequencies. In addition, coded OFDM is resistant to channel impairments such as multipath fading or narrowband interference. Because the coded information is spread across all the carriers, if a subset of the carriers is lost, the information can be reconstructed from the error correction bits in other carriers.

BACKGROUND: 802.11 MAC LAYER

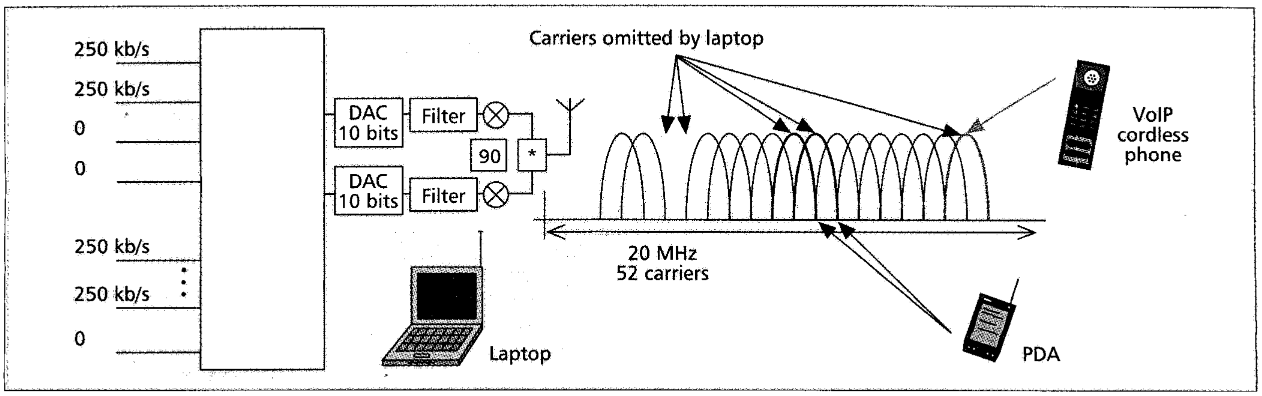
Access methods for wireless channels fall into three general categories: contention methods, polling methods, and time-division multiple access (TDMA) methods. 802.11a is based primarily on contention methods, with some polling capabilities as well. Contention systems such as IEEE 802.11 use heuristics (e.g., random backoff, listen-before-talk, and mandated interframe delay periods) to avoid (but not completely eliminate) collisions on the wireless medium. IEEE 802.11 also employs a beacon message that can be asserted by the access point and allows the access point to individually poll selected stations for sending or receiving data. The duration of the polling period is controlled by a parameter set by the access point and contained within the beacon message.

Contention systems are well suited to asynchronous bursty traffic. These systems work particularly well when the burst sizes are comparable to the natural packet size of the medium, or small multiples of the natural packet size. Slotted systems are well suited to isochronous applications that have a need for continuous channel bandwidth, although they may have extra overhead in comparison to contention systems when carrying asynchronous bursty traffic.

Another MAC layer consideration is whether there is a dedicated central controller such as an access point (AP) or base station. 802.11a uses



■ **Figure 2.** *The 802.11a PHY.*



■ **Figure 3.** *5-UP can provide scalable communications.*

an AP, but has a fallback method for when there is no centralized controller (ad hoc mode). However, the operation of the network is more efficient with an AP present.

An Extension to 802.11a Is Needed

The 5 GHz 802.11a standard offers higher data rates and more capacity than 802.11b. However, to provide a complete solution for wireless home networks, 802.11a needs to be extended to address remaining challenges. For example, the present standard does not support differing device/application types; nor does it enable a unified network that allows a single gateway or access point to support all the devices within a home. A cordless phone is a good example of such a device. It does not require a high data rate but must provide high-quality sound and error-free transmission. As things stand now, there are only two ways to implement the phone in a standard 5 GHz wireless network. You can make the phone a full 54 Mb/s device and have it share time at a low duty cycle. This is an expensive solution for a cordless phone and draws high peak power while transmitting or receiving.

The second solution is to transmit at a data rate close to the cordless phone's natural rate, and make the rest of the network nodes wait for it to get off the air. This is highly inefficient and greatly reduces the overall throughput of the network.

The best solution is to allow the cordless phone to transmit at its natural rate at the same time other nodes are transmitting at their natural rates. Unfortunately, this type of operation is not supported under any of the existing 5 GHz wireless network standards. An extension to 802.11a that allows overlaying transmissions using OFDM techniques [5, 6] has been proposed and is described in this article.

The 5 GHz Unified Protocol

The 5 GHz Unified Protocol (5-UP) proposal extends the OFDM system to support multiple data rates and usage models. It is not a new standard, but an enhancement to the existing IEEE standard that would permit cost-effective designs in which everything from cordless phones to high-definition televisions and personal computers could communicate in a single wireless multimedia network with speeds up to 54 Mb/s. 5-UP achieves this by allocating the carriers within the OFDM signal on an individualized basis. As with the background on the existing standards, we can describe the 5-UP protocol by examining its PHY layer first, and then the MAC layer. Many of the elements of the MAC layer will be seen to be outgrowths of restrictions within the PHY layer.

5-UP PHY Layer

5-UP provides scaleable communications by allowing different nodes to simultaneously use different subsets of the OFDM carriers. This is intuitive, and can be seen as an advanced frequency-division multiple access (FDMA) system. Most OFDM equipment can support this quite easily.

An example is shown in Fig. 3. In this figure, the laptop, PDA, and voice over IP (VoIP) phone are simultaneously transmitting to an access point (not shown). The laptop device generates its OFDM signal using an inverse fast Fourier transform (iFFT). It would be simple for this device to avoid transmitting on some of the carriers by zeroing out some of the inputs to the iFFT and using only the remaining inputs to transmit data. Low-data-rate devices can then occupy the slots that were omitted by the laptop. In the case shown in Fig. 3, the PDA makes use of two of the omitted carriers, while the VoIP phone makes use of one.

At the receiving side, the radio would look similar to that shown for the laptop. All carriers can be simultaneously received by the access point and recovered through its single FFT-based receiver. The access point must then group the parallel outputs of the FFT into the separate streams. Finally, when the access point transmits to the other nodes, it can use a single iFFT to simultaneously create all the carriers. Each of the other nodes can receive only its subset of carriers, discarding the carriers intended for a different node.

The great advantage to this approach is that both the analog and digital complexity required in the radio scales with the number of carriers that can be transmitted/received. In the ultimate case of just one carrier, the radio becomes a single-carrier BPSK or QPSK radio, transmitting at 1/52 the output power required to achieve the same range with a full 52-carrier radio. Table 1

Data rate	No. carriers	Modulation	Tx power average	Tx peak/	ADC/DAC	FFT size
125 kb/s	1	BPSK	0.8 mW	~1	4 bits	None
750 kb/s	1	16 QAM	0.8 mW	~1.4	5 bits	None
1.5 Mb/s	4	QPSK	3.2 mW	~4	5 bits	4
6 Mb/s	8	16-QAM	6.4 mW	~8	6 bits	8
12 Mb/s	16	16-QAM	12.8 mW	~16	7 bits	16
36 Mb/s	48	16-QAM	40 mW	~48	8 bits	64
54 Mb/s	48	64-QAM	40 mW	~48	8 bits	64

■ **Table 1.** *Tx power based on regulations for the lower 100 MHz of the U.S. UNII band.*

highlights the relative analog and digital complexity required to achieve a given data rate.

5-UP enables the building of radios with a broad range of complexity, which in turn results in a range of power and price points that serve a number of different data rate requirements, allowing all to function simultaneously and efficiently in a high-data-rate system. Table 2 lists examples of the data rates and applications that can be met using various modulations and numbers of carriers.

Data rate	Applications	Carriers	Modulation
125 kb/s	Cordless phone, remote control	1	BPSK
1.5 Mb/s	High fidelity audio	2 or 4	16-QAM or QPSK
12 Mb/s	MPEG2 video, DVD, satellite, xDSL, cable modem, data network	12, 16, or 32	64-QAM, 16-QAM, or QPSK
20 Mb/s	HDTV, future cable or VDSL broadband modem	18 or 27	64-QAM or 16-QAM

■ **Table 2.** *Data rate and application examples with various modulations and numbers of carriers.*

5-UP PHY Layer Constraints

While the evolution from an OFDM system to an advanced FDMA system is intuitive, there are a number of constraints required to make it work. These constraints come from the close spacing of the carriers (required to achieve high efficiency) and practical limitations in the design of inexpensive radio transceivers.

Frequency Control

In order for an access point to receive multiple signals simultaneously, the separate transmitting nodes must transmit their signals with well-matched subcarrier frequencies. In an OFDM system based on the IEEE 802.11 standard, the subcarriers must be spaced ~300 kHz apart. On a 5 GHz carrier, an inaccuracy of 30 parts per million (ppm) would cause a subcarrier to be transmitted halfway into the adjacent subcarrier, making it impossible to receive either signal.

In practice, the signals coming from different transmitters need to be frequency-accurate to one another within a few ppm to preserve sufficient orthogonality (isolation) between the carriers. While this may appear daunting, current OFDM systems must similarly extract the frequency offset of the incoming signal to within a few ppm, and must correct the frequency offset before demodulating the signal with the FFT processor. The difference in 5-UP is that when carriers are overlaid, the frequencies of independent transmitters need to be locked to each other before transmission. Then the access point can do a final uniform correction of all the carriers within its receiver to align the complete set of carriers to its FFT frequency bins.

The required frequency locking between transmitters may be accomplished by locking all the transmissions to the frequency transmitted by the access point. This can be accomplished as follows. When the access point transmits, all nodes are able to receive the signal and extract the frequency offset of the access point relative to the node's local frequency reference (crystal). Once this frequency offset is known, the node can precompensate the transmit signal in the digital domain to force the transmitted frequency to match what was received from the access point. Although the access point's frequency might not be correct in absolute terms, it is the relative carrier frequency spacings, not the absolute carrier frequencies, that must be accurate. As long as all nodes lock their carriers to this reference, the frequency spacings between all carriers will be correct.

There is a trade-off between the accuracy of the frequency locking and the required power control accuracy (described later). When the frequencies are very accurate, the individual carrier frequencies are close to orthogonal, and there is great isolation between carriers. Therefore, even if one carrier is much stronger than the others, they can all be received. Less accurate frequency lock causes the signals to lose their orthogonality. Because the carriers are not as well isolated, it is not possible to recover the information in all the carriers if some of the carriers are stronger than others. In general, ±1 ppm is an achievable frequency accuracy, and allows reasonable tolerance in power control (±3 dB).

Timing Control

In order to efficiently process all the received signals in the same FFT-based receiver in the access point, all signals must arrive time-aligned within the guard time allocated for multipath echoes in the environment. Misalignment in the time of arrival of overlaid OFDM signals equals

The issues of frequency, timing, and power control are unique to the period of time during which multiple nodes are transmitting simultaneously. They are not an issue when a single node is transmitting, such as when the access point is sending data to all the nodes simultaneously.

only a mismatch of the guard intervals. Given a guard interval of 800 ns (as specified by 802.11a) and indoor propagation, there is guard time to spare. In typical indoor environments, time alignment within ± 100 ns would be sufficient. For short ranges (~ 30 m), overlaid transmissions can be timed off the received signals from the AP. This works because the maximum "flight" time differences between nodes will not be large.

For longer ranges, closed-loop timing control can be implemented in which the AP advises nodes to begin transmissions sooner or later. The AP can send commands in data, packets adjusting packet transmit timing to each of the nodes in a closed loop fashion.

POWER CONTROL

As described earlier, frequency inaccuracies can compromise orthogonality, requiring carriers from different transmitters to arrive with similar signal strengths. It is theoretically possible to recover perfectly frequency-locked signals with infinitely large received signal strength differences. However, all practical receivers have dynamic range limitations, such that some degree of power control would be necessary in any case.

Transmit power control is not a new concept in wireless systems. The code-division multiple access (CDMA) cellular system [7] implements very sophisticated power control, in which the power from different transmitters is matched within 1 dB at the receiver. Such excellent matching in power is required because the CDMA codes used for the different users are not perfectly orthogonal. In fact, the CDMA codes used are much less orthogonal than the OFDM carriers, even with ± 1 ppm frequency errors between carriers. Therefore, power control within ± 3 dB is sufficient for 5-UP.

Historically, accurate power control has been implemented using closed-loop feedback from the receiver. In other words, the receiving AP would send back messages to each transmitting node indicating if the node's transmit power should be increased or decreased. However, because 5-UP does not require highly accurate power control, an open loop scheme could also be chosen. In that case each node would base its transmit power on the power level it can receive from the access point. For example, if the signal from the access point is strong, the path loss is low, and the node should transmit at a low power. If the signal from the AP is weak, the transmit power should be high to overcome the large path loss.

The issues of frequency, timing, and power control are unique to the period of time during which multiple nodes are transmitting simultaneously. They are not an issue when a single node is transmitting, such as when the access point is sending data to all the nodes simultaneously. In this case, the carriers within the signal from the access point arrive at all the nodes with perfect frequency spacing, equal amplitudes, and perfectly matched timing.

Note that perfect alignment of timing and received power from multiple transmitters can only be achieved at one receiving location at any given time. Therefore, when transmissions from multiple nodes are overlaid, all of the overlays should be destined for the same receiver. In the 5-UP system, having nodes that are using a subset of the carriers send all their information to the access point ensures this. This is the desired destination for much of the traffic anyway, since the access point represents the bridge to the wired network. For messages that are intended for other wireless devices, it is simple for the access point to forward those messages to the appropriate device in the next time period. This type of centralized message routing is called for in the current 802.11 protocol when an access point is present.

NARROWBAND FADING AND INTERFERENCE CONTROL

One disadvantage to using the carriers independently is that narrowband interference or fading can wipe out the complete signal from a given transmitter if it is using just one or a few carriers. Under those conditions, no amount of coding will allow the missing signal to be recovered.

Two solutions are well known to make narrowband signals more robust. The first is to employ antenna diversity. Radios can be built that can select between one of two antennas. If the desired carriers are in a fading null at one antenna, then statistically they are not likely to be in a null at the other antenna. Effective diversity gains of 8 to 10 dB are normally observed for two antenna systems.

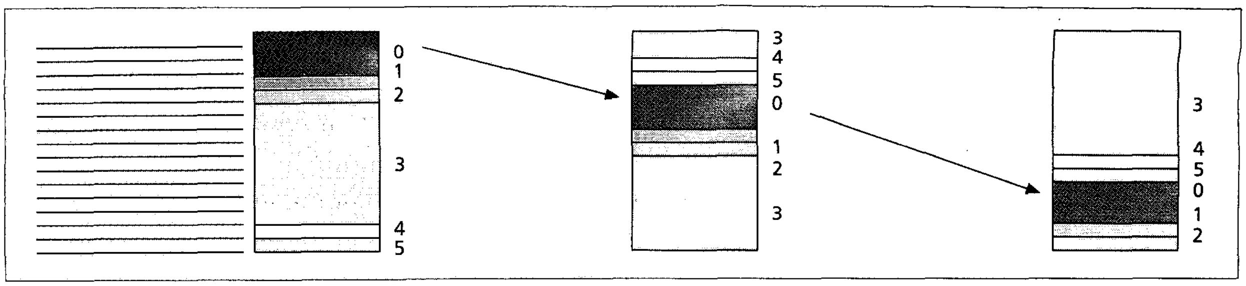
A second way to provide robustness to narrowband fading and interference is to "hop" the subcarriers in use over time. This approach will work even for the case in which only one subcarrier is used at a time. For example, the node could transmit on subcarrier 1 in the first time period, then switch to subcarrier 13 in the next period. Packets lost when the node is on a frequency that has interference or fading could be retransmitted after the next hop. Several such hopping nodes could be supported at the same time, hopping between the same set of subcarriers on a sequential basis. A similar arrangement could be used for nodes that use multiple subcarriers simultaneously, hopping them all in contiguous blocks, or spreading them out and hopping the entire spread of subcarriers from one channel set to another over time (Fig. 4).

A carrier allocation algorithm that is more intelligent than blind hopping can also be implemented. Narrowband fading and interference are likely to affect different nodes within a network differently due to the various nodes' locations. Thus, a given subcarrier may work poorly for some of the nodes, but it might work well for other nodes. The subcarriers could therefore be intelligently allocated, swapping the assignments between nodes until all nodes are satisfied.

THE 5-UP MAC

The 5-UP protocol may readily be adapted to work with existing industry standard protocols such as 802.11a. Figure 5 shows a picture of the 5-UP frame as it would be imbedded into an 802.11a system. In the figure, the different rows represent different carriers, while the columns represent different slots in time.

To make the 5-UP protocol work three fundamental things are required.



■ **Figure 4.** *The progression of carrier assignments over subsequent frames.*

First, there must be a way to carve out time during which the 5-UP overlaid communication can take place. In the case of 802.11, this can be done using the point coordination function (PCF) beacon. The original definition of 802.11 included two medium access control mechanisms. These are the distributed coordination function (DCF) and the PCF. DCF is Ethernet-like, providing for random channel access based on a listen-before-talk carrier sense multiple access (CSMA) technique with random backoffs. This is the most commonly used access mechanism in current 802.11 equipment.

The PCF access mechanism is based on centralized control via polling from the access point. In this access mode, all nodes are silent until they are polled by the access point. When polled by the access point, they can send a packet in return.

Two beacons are used to define the time during which the PCF access mechanism is in operation (the contention-free period) rather than the DCF mechanism. The PCF beacon announces to all the nodes that the polling access period is beginning. When nodes receive this beacon, they do not transmit unless they receive a poll from the access point that is addressed specifically for them. The end of the PCF (contention-free) period is signaled by a contention-free end beacon (CF-End).

In an 802.11 system, the contention free periods are typically periodic, allowing for nearly isochronous communication of some portion of the traffic.

The PCF beacon can be used to reserve a time period during which all legacy nodes will remain silent and the 5-UP protocol can operate. Once the PCF beacon has been transmitted by the access point, all nodes must remain silent as long as they are not requested to transmit by a valid poll message. Because overlaid 5-UP traffic will not appear to be valid poll messages, legacy nodes will remain silent throughout the 5-UP period. 5-UP-enabled nodes can then be addressed using the 5-UP protocol without interference from legacy nodes.

After the 5-UP period has ended, the access point can send an 802.11 CF-End message, as defined in the standard, to reactivate the 802.11 nodes that were silenced by the initial PCF beacon. Following the CF-End message, communication would return to the nonoverlaid 802.11a method.

In this manner the channel can be time shared between traditional 802.11a operation and 5-UP operation. Legacy nodes will participate only in the 802.11a period, and will not transmit or receive any valid packets during the 5-UP period. Nodes that can only operate during the 5-UP period, such as nodes that can only operate on a subset of the carriers, will not be able to transmit or receive during the 802.11a period, but will be active during the 5-UP period. Finally, nodes that are able to handle both 802.11a and 5-UP messages can transmit or receive in either period. The access point can adjust the timing of the PCF and CF-End beacons to balance the traffic requirements of 5-UP and legacy 802.11a nodes.

The second requirement for embedding the 5-UP protocol into the 802.11a protocol is to ensure that all devices know when they need to transmit in the 5-UP overlaid fashion and when to transmit according to the 802.11a methods. For nodes that understand the 5-UP protocol only, or can use only a subset of the carriers, all communication outside of the 5-UP period will be indecipherable and will appear as noise. However, when the 5-UP period arrives, the 5-UP beacon transmitted at the beginning of this period will be intelligible. The 5-UP beacon is transmitted on each carrier individually such that even a single-carrier device can receive and understand it. This beacon includes information on the length of the 5-UP period and when the next 5-UP period is scheduled. Once synchronized, nodes that communicate only during the 5-UP period can sleep during the 802.11a periods.

Nodes that do not understand the 5-UP protocol will know not to try to transmit during the 5-UP period, as described above. Nodes that understand both the 5-UP and 802.11a protocols can understand all the packets that are transmitted, gaining information from both sets of beacons and potentially transmitting and receiving during both periods of operation.

Direct peer-to-peer communication or communication with the access point can be allowed in the nonoverlaid period. However, during the 5-UP overlaid period, only communication to or from the access point is allowed.

The third basic requirement is that 5-UP nodes must be able to request service, and must be instructed which carriers, hopping patterns, and time slots they should use. The 5-UP beacon is transmitted on each carrier such that even a single-carrier node can interpret this beacon no matter to which carrier it has tuned. The beacon includes information about which carriers and time slots are available to request service or associate with the network. As shown in Fig. 5, there are uplink slots (transmitting to the access point)

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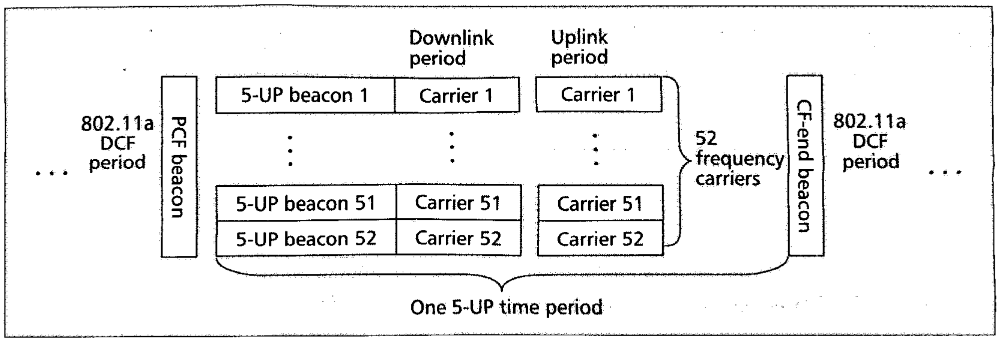

■ **Figure 5.** *The 5-UP frame.*

and downlink slots (receiving from the access point). The node requesting service waits until it gets a response during a downlink slot. The response includes the carriers and time slots that will be allocated for traffic for that device. It also would indicate the hop pattern and timing if the network is operating in a hopping mode.

Some information, such as the time reference and when the overlaid communication period begins and ends, needs to be transmitted on each carrier; however, other information such as which time slot is assigned to which node for a given carrier is unique to each carrier. Information unique to a given node (e.g., sleep/wake information) only needs to be transmitted on one of the carriers assigned to that node.

CONCLUSION

5-UP will provide enhancements to the 802.11a standard that will enable home networking to reach its ultimate potential with scalable communications from 125 kb/s through 54 Mb/s. Robust, high-rate transmissions are supported in a manner compatible with 802.11a, while allowing low-data-rate low-cost nodes to communicate with little degradation in aggregate network throughput. 5-UP allows the construction of radios tuned to the performance requirements of any application from 125 kb/s up, in increments of 125 kb/s.

With 5-UP enhancements, each node can get a private, unshared channel with no collisions, fewer lost packets, no backoffs, and no waiting for the medium to free up. 5-UP requires no big buffers because transmission rates can closely match required data rates, making 5-UP a natural for multimedia support and quality of service (QoS).

In sum, the 5 GHz Unified Protocol is a definitive step forward in the development of a new higher-functionality wireless LAN standard for home networking that will allow all wireless devices, regardless of their bandwidth requirements, to operate on the same network. 5-UP will enable QoS, bandwidth reservation, and data rates up to 54 Mb/s, while at the same time providing scalable cost, power usage, and bandwidth allocation.

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BIOGRAPHIES

BILL MCFARLAND (billm@atheros.com) received a B.S.E.E. from Stanford University in 1983, and an M.S.E.E. from the University of California at Berkeley in 1985. He joined Hewlett Packard Laboratories in 1985. While at HP Labs, he worked on integrated circuits for high-speed test equipment and fiber optic communications. From 1994 to 1999 he managed the radio circuits research group at HP Labs. In 1999 he joined Atheros Communications where he is director of algorithms and architecture. He has published over 20 papers and holds eight patents.

GREG CHESSON earned degrees in computer science at the University of Illinois, was a member of technical staff at Bell Laboratories from 1977 to 1982, and was a chief scientist at SGI from 1982 to 2000. He developed early Datakit protocols, the XTP and ST protocols, the GSN (Hippi-6400) network, contributed to many VLSI, system, OS, and network projects, and presently serves as director of protocols at Atheros Communications.

CARL TEMME is director of product management at Atheros Communications. He has over 15 years of experience in wireless product development and has previously served as a senior manager with the Electronics and High Technology Product Development practice at Andersen Consulting and as Wireless Data product line manager for VLSI Technology. He holds a Master's degree in engineering management from Stanford University and a B.S.E.E. from the University of California, Davis.

TERESA H. MENG received her Ph.D. in EECS from the University of California, Berkeley in 1988. She joined the faculty of the Electrical Engineering Department at Stanford University in 1988, where she is now a professor and the Robert Bosch Faculty Fellow. In 1998 she took leave from Stanford and founded Atheros Communications Inc., which provides the core technology to deliver ubiquitous high-performance wireless connectivity and networking. Awards and honors for her work include an NSF Presidential Young Investigator Award, an ONR Young Investigator Award, and an IBM Faculty Development Award. She was named one of the Top 10 Entrepreneurs by Red Herring in 2001.