The Evolution of Cellular Backhaul Technologies: Current Issues and Future Trends

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***Abstract*—The rapid increase of the number of mobile subscribers as well as the deployment of 3G technologies are putting strain on mobile backhaul operational expenditures (OPEX) which amount to 20-40% of total mobile operator's OPEX due to their reliance on T1/E1 copper lines. For these reasons, the current backhaul systems, a term commonly used to describe connectivity between base stations and radio controllers, are increasingly integrating more cost-effective, packet switched technologies, especially Ethernet/Internet technologies. In addition, Wi-Fi and WiMAX are emerging as promising backhaul solutions and initial findings have demonstrated their feasibility. However, the notion of network migration unavoidably raises new technical challenges relevant to aspects of TDM and packet network timing synchronization, QoS, and packet efficiency. This survey aims to provide a comprehensive study of state-of-the-art circuit switched and emerging packet switched backhaul technologies based on research articles and standard documents. For packet switched backhaul, we focus on the practically important Pseudowire approaches which are used to transport TDM services over packet switched networks. We also discuss the features and research findings on the use of Wi-Fi and WiMAX technologies which illustrate their potential for rapid and cost-efficient backhaul deployment. Finally, we highlight some open issues relevant to timing synchronization in wireless mesh backhaul and femtocells deployments, which offer a rich ground for further research.**

***Index Terms*—Backhaul networks, GSM, Mobile networks, circuit switching, packet switching, time synchronization.**

I. Introduction

MOBILE backhaul is a term commonly used to describe connectivity between base stations and radio controllers in cellular systems over a variety of transport media. As illustrated in Figure 1, today's backhaul relies mostly on three physical mediums: copper, optical fiber and microwave radio links. In the US, for example, leased T1/E1 copper constitutes approximately 90% of backhaul implementations followed by microwave links (about 6 %) and optical fibers (about 4 %) (1). Optical fibers may be deployed in dense urban and suburban locations, which are considered high traffic areas. On the other hand, microwave radio and satellite links are utilized in locations where wired backhauls are difficult to deploy. Leased T1/E1 copper lines dominate the backhaul solutions, as they provide suitable support for voice traffic, with deterministic QoS, low latency and low delay variations (jitter). In addition, timing and synchronization is inherently available from T1/E1 lines, which is a necessary requirement in cellular systems. Up to now, one to two leased T1/E1 copper lines have been considered sufficient per cell site to handle 2G traffic including voice and short message service.

Recently, however, the required backhaul capacity has significantly increased due to the increasing number of mobile subscribers and the availability of mobile high-speed data services. The increasing number of mobile subscribers have resulted in a significant growth in the number of deployed base station sites and associated T1/E1 connections. In the US, for example, the number of base stations went up from 30,045 in 1996 to 213,299 in 2007 (1). On the other hand, the implementation of GPRS and EDGE requires four times the number of leased T1/E1 copper lines, compared to five years ago and is expected to be as much as eight to sixteen times when HSPA and LTE 4G technologies are fully deployed. As a consequence, leased T1/E1 copper, which price increases linearly with capacity, is not a cost efficient choice for backhaul. Today, the backhaul expenditure remains one of the greatest concerns for mobile operators. Due to their significance and impact, some have recently referred to it as the "telecom global warming" (2). This problem caused some equipment providers to resort to workforce reductions in the access network business and to shift resources to the mobile backhaul area (3), and motivated many mobile operators to migrate towards cost effective packet-based backhaul solutions.

In this survey, we offer a comprehensive study of the ongoing migration from legacy to emerging backhaul network technologies, which is to the best of our knowledge, the first survey in this emerging area. Our survey presents a thorough examination of numerous cellular and Internet standards as well as relevant publications from academia and industry. Based on the survey study, we unveil the potential and the challenges of evolving backhaul solutions using packet switched networks and inexpensive wireless technologies, such as Wi-Fi. We show that the migration to new technologies raises new technical challenges relevant to QoS, packet efficiency, and timing synchronization. From Pseudowire to wireless mesh, we identify attractive features of the emerging solutions, with respect to their low cost and availability. Especially interesting are the recent implementations of wireless mesh backhaul solutions using vendors' proprietary protocols in commercial sites (4). Also the current "all-IP" trends in 4G networks and femtocells carry interesting research challenges for wireless backhaul.

This survey is organized as follows. In Section II, we present traditional and emerging backhaul technologies. We start by explaining advantages and shortcomings of traditional backhaul technologies (e.g., Leased T1/E1 copper, optical fiber, microwave and satellite). We then discuss Pseu-

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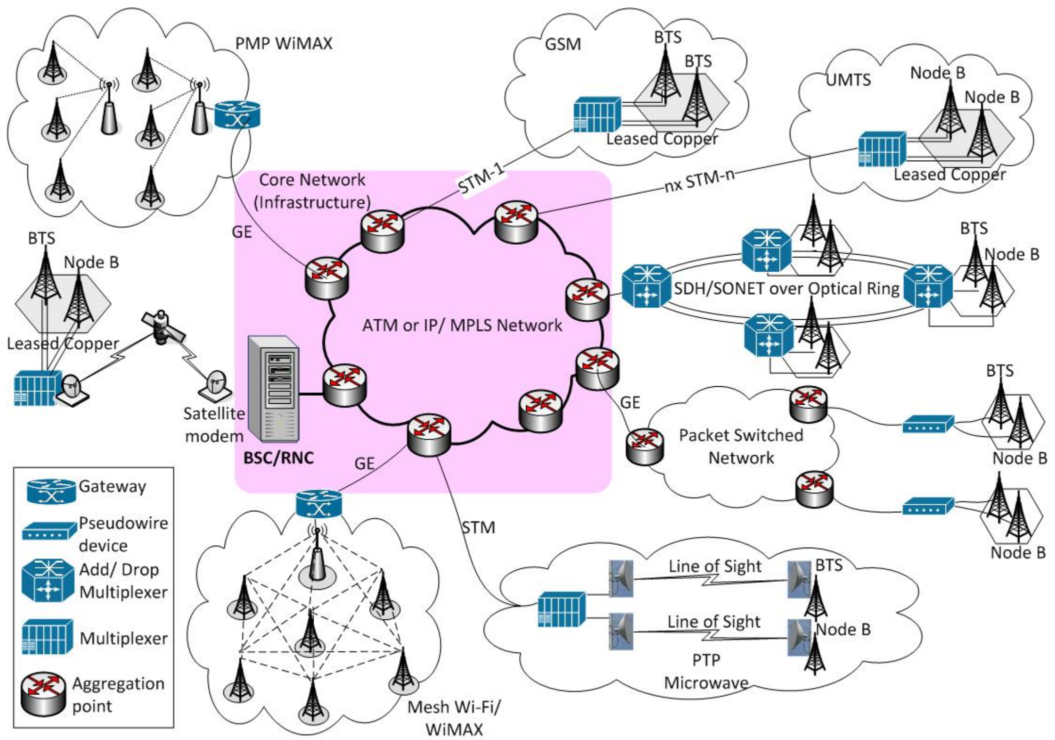


Fig. 1. Backhaul Network Technologies (BTS: Base Transceiver Station, BSC: Base Station Controller, RNC: Radio Network Controller, PTP: Point-to-Point, PMP: Point-to-MultiPoint, GE: Gigabit Ethernet)

dowire solutions based on emerging backhaul technologies for transporting Time Division Multiplexing (TDM) over packet switched networks along with the associated technical challenges. In Section III, we study prospective wireless technologies for backhaul solutions based on Wi-Fi and Worldwide Interoperability for Microwave Access (WiMAX). In Section IV, we survey timing and synchronization in current and emerging backhaul solutions. Section V summarizes the main findings from this survey by comparing of all presented backhaul technologies, and discussing future trends and open issues. Section VI concludes the paper.

II. From Traditional to Emerging Backhaul Technologies

In this section, we start by addressing wired backhaul networks based on copper cables and optical fibers, give an overview of wireless backhaul technologies such as microwave and satellite, and finally conclude the section by an overview of the Pseudowire technology.

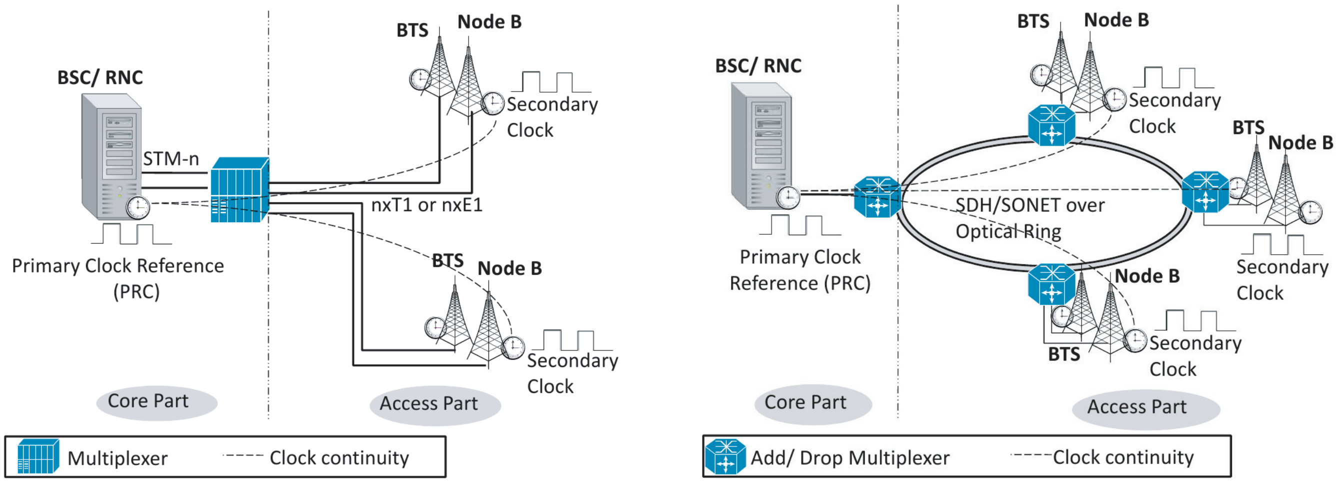
A. Copper and Optical Fiber Backhaul Networks

Copper cables are the traditional backhaul medium between Base Transceiver Stations (BTSs) and Base Station Controller (BSC). TDM techniques using the so-called Plesiochronous Digital Hierarchy (PDH) are prevalent techniques which allow multiplexing multiple voice channels from base stations and transporting them to the BSC in different time slots. In this regard, there are two standard plesiochronous hierarchies which are very similar in their operation but primarily differ in the delivered bit rates: the T-carriers (T1,T2,...,T4) and E-carriers (E1,...,E5). For instance, T1 links operate on 1.544 Mbit/s while E1 connections operate on 2.048 Mbit/s. The T-carriers are primarily used in North America and Japan while E-carriers are used in Europe and the rest of the world. T1/E1 connections can be deployed as point-to-point systems or over PDH multiplexing systems. The T1 frame consists of 24 time slots of DS0; each can support a 64 kbit/s PCM voice call. Typically one DS0 is dedicated for signaling; therefore, without any voice compression, a T1 line can carry 23 voice calls. For E1, there are 32 time slots of DS0 where 30 time slots are used for voice communications and the other two are used for frame synchronization and signaling[1]. For better bandwidth utilization, voice compression techniques such as G.729 and EVRC are introduced to compress 64 kbit/s PCM encoded voice streams, leading to a throughput gain of four folds (i.e., one DS0 can support 4 PCM streams using compression). As a result, one T1 can support 23x4 = 92 voice calls and one E1 can support 30x4 = 120 voice calls.

Optical fibers. In many cases leased T1/E1 copper lines from multiple sites are merged at a multiplexer which multiplexes lower rate T1/E1 connections into higher rate optical fiber connections such as STM-1 (155.52 Mbit/s), STM-4 (622 Mbit/s) and STM-16 (2.4 Gbit/s) as shown in Figure 2(a). The STM standards are used as Synchronous Optical Networking (SONET) in North America and as Synchronous Digital Hierarchy (SDH) in Europe and the rest of the world[2]. As also shown in Figure 2, TDM backhaul can distribute timing information throughout the network. In cellular systems

[1] Time slot 0^{th} is dedicated for frame synchronization and time slot 16^{th} is dedicated for signaling.

[2] SDH and SONET are standardized multiplexing protocols for transferring digital streams over point-to-point optical fibers and radio links, depending on the specific operator choices.



(a) TDM Backhaul Network Using Aggregation of Point-to-Point Leased Lines

(b) TDM Backhaul Network Using SDH/SONET over Optical Ring

Fig. 2. TDM Backhaul Networks (BSC: Base Station Controller, RNC: Radio Network Controller, BTS: Base Transceiver Station)

such as GSM, the primary reference clock (PRC) (i.e., the master clock signal) maybe hosted by the mobile switching center (MSC) or at the base station controller sites[3] and the slave clocks (a.k.a, secondary clocks) at the base station sites are traceable to the primary clock reference. The issue that arises now is that as we move towards packet switched networks using Pseudowire technologies, timing information is lost. This is a serious issue and if not mitigated, base stations may not be able to control their radio frequencies properly and handoffs may result in dropped calls. Network synchronization is very important for proper handover process in cellular networks. More details of timing and synchronization aspect will be discussed in Section IV-B.

SDH/SONET over optical fibers can also be implemented in ring topologies, as shown in Figure 2(b). The add/drop multiplexer is an important element of an optical fiber network which combines or multiplexes several lower-bandwidth data streams into a single beam of light. In addition, it can add one or more lower-bandwidth signals to an existing high bandwidth data stream, while at the same time, extract or drop other low bandwidth signals by removing them from the stream and redirecting them to other network paths. The use of SDH/SONET fiber rings can only be justified at the cellular sites when certain cost conditions are satisfied, as discussed in (5), where it was suggested to replace T1 connections at the cellular sites based on a multi-parameter backhaul cost model. The parameters include the distance between the cell site and the add/drop multiplexer, the number of T1 connections per site, and the number of cell sites to be connected via the fiber ring. The results indicate that a ring should at least serve 4 cell sites for cost efficiency and that optical backhaul can achieve significant cost savings (27% or more) for cell sites with 4 or more T1 connections.

[3]In some case (e.g., GPS primary clocks), the primary clock reference is distributed and is directly available at the base station sites.

B. Microwave and Satellite Wireless Backhaul

Microwave radio links are an alternative choice for wired backhaul links especially in geographically challenging areas where wired connections are not available. Microwave transmission can be carried out in various frequency bands including licensed (6 GHz to 38 GHz) and unlicensed (2.4 GHz and 5.8 GHz) bands. Using unlicensed bands can reduce Capital Expense (CAPEX) but raises radio interference issues. The used frequency spectrum affects bandwidth capacity and distance coverage; the higher the frequency, the greater the bandwidth capacity and the shorter the coverage range[4]. In all cases, the presence of Line of Sight (LOS) between cell cites and aggregation points (e.g., at a SONET ring) is required and hence microwave is limited to short distance transmission when used in metropolitan environments. However, in rural environments, when a LOS is present, microwave transmission can be quickly installed to cover long distances. Compared to T1/E1 copper links, implementing microwave links results in higher CAPEX due to equipment costs and spectrum licensing fees, however they are likely to incur less OPEX over time.

Microwave can be implemented in the Point-to-Point (PTP), Point-to-Multipoint (PMP), or proprietary multihop configurations for better coverage. Whereas the PTP system requires a radio and antenna at the end of every wireless link, in PMP, one radio and antenna at an aggregation point are sufficient to serve a number of cell sites. The digital transmission technique over microwave links can be based on PDH (i.e., one or more T1/E1), SDH/SONET or Ethernet (Gigabit Ethernet protocol). Figure 3 shows the PTP microwave backhaul network with increased distance coverage as a result of implementing a multihop architecture. Research results in (7) suggest that using PTP microwave links to backhaul traffic from cell sites onto leased T3 copper links can result in significant savings compared to using leased T1 copper backhaul. In addition,

[4]Some products (6) can provide wireless Gigabit Ethernet Point-to-Point (PTP) communications with throughput up to 1.25 Gbit/s in the 71-76 GHz and 81-86 GHz bands, and rates up to 170 Mbit/s in the 17.7-19.7 GHz microwave band.

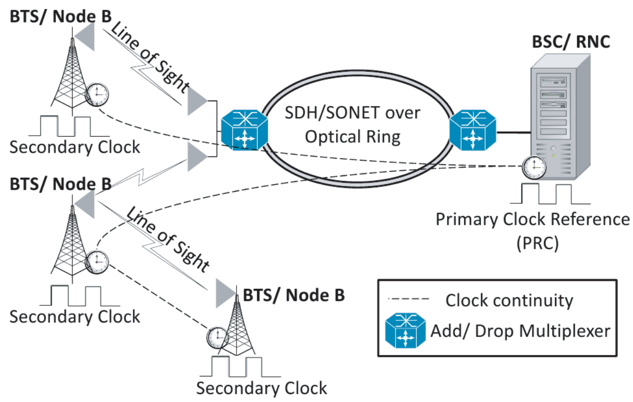


Fig. 3. Point-to-Point Microwave Backhaul (BTS: Base Transceiver Station, BSC: Base Station Controller, RNC: Radio Network Controller)

deploying a PMP topology in microwave backhaul network can only be cost efficient if at least 5 cells are served by each PMP system.

Satellite backhaul offers a solution for locations where no other backhaul technologies are feasible. The transmission over satellite links for cellular backhaul is mostly based on T1/E1 techniques. Advantages of satellite links are their short installation times and flexible coverage while their major drawbacks are their high cost and long propagation delay. For instance, based on (8), typical propagation delays for satellite links are around 270 ms plus processing delay, which are higher than the acceptable end-to-end delay for voice services of 250 ms. In addition, the cost for the transponder bandwidth of 768 kbit/s (about a half of T1) on a full time basis is $3,000 - $6,000 per month and for an equivalent of full T1 bandwidth (1.544 Mbit/s) is $5,000 - $12,000 per month (data as of 2002). To alleviate such high expenses, usage based billing mechanisms was proposed to help reducing the incurred costs. This is achieved by using Demand Assigned Multiple Access (DAMA) techniques which dynamically allocate bandwidth resources based on actual requests from the users.

The feasibility of satellite cellular backhaul was demonstrated in challenging sites such as islands and remote locations where no wired solutions are available. For instance, in (9), the authors presented a case study of using satellite as cellular backhaul in the Federated States of Micronesia in the Pacific Ocean. They showed that the satellite backhaul is much more cost effective than deploying costly submarine cables. Another example is the satellite backhaul trials which took place in rural areas in France (10). The results of the trials not only demonstrated the feasibility of the satellite link but also that the traffic in forward and reverse links is symmetrical which offers useful input to satellite bandwidth management.

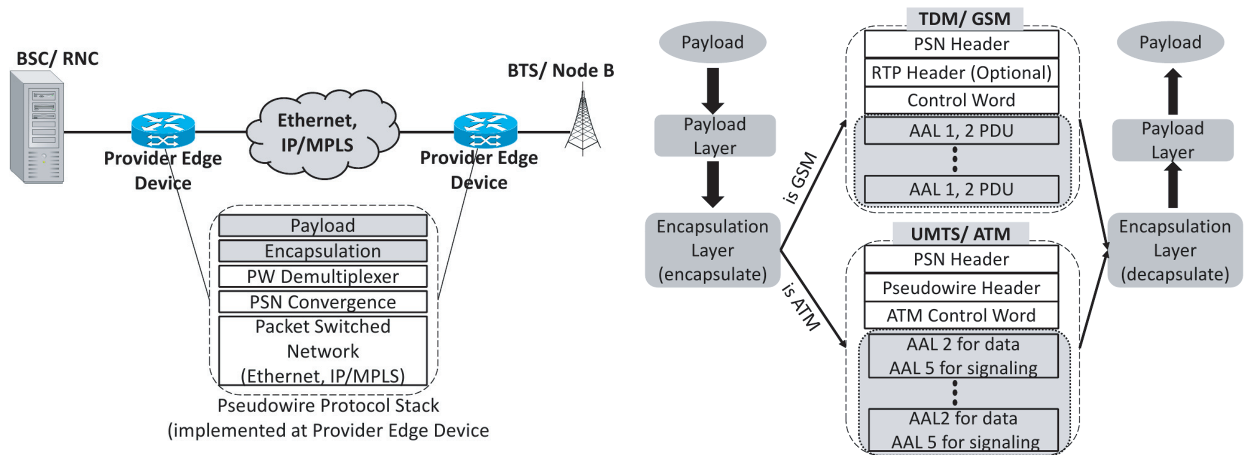
C. The Pseudowire Framework

Traditional backhaul technologies described so far majorally rely on circuit switched technologies and hence can not be directly connected to packet networks. As the next generation LTE systems and alike are expected to natively use packet-based backhauls, the *Pseudowire framework* was introduced as a backhaul technology to transport traditional services, e.g. TDM over packet switched networks, e.g. Ethernet, IP or MPLS (11). Relevant to our discussion, the mechanism of transporting TDM traffic over a packet switched network is referred to as *circuit emulation*, a.k.a, "TDM Pseudowire". It is widely accepted that Pseudowire techniques not only offer better network integration over unified packet switched cores, but they also offer significantly lower cost per megabit, with a cost/megabit ratio for a T1/E1 circuit to Ethernet of approximately 6 to 1 (12)). In fact, several standards were published by the IETF to date, such as RFC 5086 and RFC 5087 (13; 14) which address circuit emulation for GSM backhaul; RFC 4717 and RFC 4816 (15; 16) address the transport of ATM services used in UMTS backhaul over packet switched networks. Many Pseudowire standards were recently published by the IETF Pseudowire Emulation Edge to Edge (PWE3) working group which address architecture, native services (e.g., TDM), framing protocols, types of packet switched networks (Ethernet, IP, MPLS), and operational aspects. Some of these standards are listed in Table I.

TABLE I
PSEUDOWIRE STANDARDS

Standard	Description
RFC 3985	• Describes an architecture for Pseudowire • Discusses the emulation of services e.g. TDM, ATM over packet switched networks
RFC 4385	• Describes the design of a Pseudowire Control Word for use over MPLS to distinguish Pseudowire payload from a regular IP payload
RFC 4448	• Specifies the encapsulation of Ethernet payload to be carried over MPLS • Specifies the procedure for using a Pseudowire to provide a point-to-point Ethernet services
RFC 4717	• Specifies the encapsulation of ATM cells to be carried over MPLS
RFC 4816	• Describes a transparent cell transport service for encapsulating ATM cells to be carried over packet switched networks
RFC 4842	• Provides encapsulation formats for emulating SDH/SONET services over MPLS
RFC 5086	• Describes a method for encapsulating TDM bit streams to be carried over packet switched networks
RFC 5087	• Provides encapsulation details of TDM payload for specific packet switched networks e.g. MPLS, Ethernet.

Figure 4(a) illustrates how the native service payload is first processed by the encapsulation layer, the Pseudowire (PW) de-multiplexer layer and the Packet Switched Network (PSN) convergence layer. The resulting Pseudowire data is then encapsulated in the data portion of the packets traversing the packet switched network. In the context of backhaul, the Pseudowire payload types can be a packet (e.g., ATM AAL5 PDU), an ATM cell, a T1/E1 or a T3/E3 bit stream, or a structured bit stream (e.g., SDH/SONET). The encapsulation layer provides any information that is needed by the edge devices to forward packet from the packet switched network boundary to the TDM network boundary and to reconstruct the original TDM payload from the received packets (13). The PW Demultiplexer layer allows delivering multiple Pseu-



(a) Pseudowire Protocol Architecture,
(BSC: Base Station Controller, RNC: Radio Control Network)

(b) Pseudowire Payload Encapsulation (AAL: ATM Adaptation Layer)

Fig. 4. Pseudowire Protocol Architecture and Payload Encapsulation, (PSN: Packet Switched Network)

dowire connections over a single packet tunnel. The PSN convergence layer allows Pseudowires to be independent of the packet switched network type while meeting the service requirements. Significant relevant functionality to backhaul networks is inherent to the encapsulation layer as described next.

The Encapsulation layer is composed of three sub-layers: Payload Convergence, Timing, and Sequencing. The main task of the payload convergence sub-layer is to encapsulate the payload. The timing sub-layer provides timing and synchronization within packet switched networks (see Section IV-B for details). The sequencing sub-layer handles out-of-order packet arrival and packet loss issues. In the context of backhaul networks, the encapsulation layer can be used to handle the GSM TDM based backhaul circuits as well as the UMTS ATM based backhaul connections. As shown in Figure 4(b), the encapsulation layer decides the type of processing depending on the payload's type(e.g., whether it is a T1/E1 bit stream or an ATM cell). For a GSM T1/E1 bit stream payload, the TDM frames are converted to packets along with some added headers, including a PSN header, a Real-time Transport Protocol (RTP) header, and a TDMoIP control word as follows,

- The PSN header may be IPv4/IPv6+UDP header or MPLS label stack.
- RTP is normally used to transport timing information across the packet switched network by providing a sequence number and a timestamp (13); but it is practically omitted due to two reasons. First, the TDM source produces a constant bit rate based on its local clock; and second, the size of the RTP header is relatively large (12 bytes) (14).
- TDMoIP control word consists of sequence number, payload length, and flags. The sequence number is used for frame re-ordering and packet loss detection while the flags are used to indicate error conditions (see (13)).

The encapsulation of TDM bit streams is not a mere packetization process since lost packets can cause service interruption and due to the packetization inefficiency incurred when encapsulating fractional T1/E1 frames (14). Usually, multiple T1/E1 frames are grouped together into one big frame before encapsulation and only the timeslots in use within each T1/E1 frame are sent (14). The AAL1 and AAL2 encapsulation techniques are used to handle the bit stream. AAL1 is suitable for Constant Bit Rate (CBR) applications where timeslots are statically allocated, while AAL2 is suitable for Variable Bit Rate (VBR) where timeslots are dynamically assigned (14). According to RFC 5087, the specific choice of AAL techniques rather than other encapsulation methods is due to three primary reasons. First, AAL mechanisms are general solutions for transporting constant or variable-rate real-time streams over packet switched networks. Second, AAL mechanisms are already deployed within and at the edge of the public telephony system. Third, the use of AAL technologies simplifies interworking with existing AAL1 and AAL2 based networks (14). These mature technologies are proven to reliably transfer voice-grade channels, data, and telephony signaling.

Similar to the encapsulation process of TDM payload, the ATM payload (see Figure 4(b)) is encapsulated with added headers including a PSN header, a Pseudowire header, and an ATM control word (15). The PSN header depends on the used tunneling technology (e.g. IPv4/IPv6 or MPLS). The Pseudowire header identifies a particular ATM service within the PSN tunnel (15). The ATM control word contains a length, a sequence number, and control bits needed to carry the service. Since the traffic flows between the Radio Network Controller (RNC) and Node B are carried over an Iub interface which includes signaling and data, signaling is handled using AAL5 while data is handled using AAL2 encapsulation rules.

Although migrating to packet switched networks for cellular backhaul offers significant advantages, it poses technical issues relevant to timing synchronization, quality of service (QoS), and packet efficiency. Due to the breadth of the details relevant to timing synchronization, we address them separately in Section IV. QoS issues arise as packet switched networks are predominantly best-effort and connection-less, which turn them difficult to offer QoS guarantees. The survey of research results on QoS in IP-based networks can be found in (17). With the inception of MPLS RSVP-TE as a connection-oriented switching paradigm, it became possible to offer end-to-end QoS with fast packet delivery in a way that is comparable to ATM networks.

Packet efficiency is another important issue that arises as large protocol overheads are added to the service payload in packet switched networks. While packet efficiency is not an issue for data packets with large payload sizes, it is a serious problem for data packets with low payloads (e.g., voice) where the packet header size is comparable to the payload size. For example, to meet the stringent delay requirement (<100 ms delay) using EVRC codec (9 kbit/s) in EV-DO cellular systems, voice packets are sent every 20 ms. This results in a voice payload of 24 bytes and a UDP/IP header of 28 bytes (20 bytes IP + 8 bytes UDP) resulting in 53% of overhead. In order to mitigate this issue, *header reduction techniques* were proposed, e.g., in (18). In addition, IETF standards widely addressed efficiency issues for VoIP traffic (e.g., RFC 2507, RFC 2508, and RFC 3095 Robust Header Compression (ROHC)). For example, RFC 2508 reduces the 40 bytes RTP/UDP/IP header to 2 bytes while ROHC reduces it to 1 byte. The RFC 2508 technique is sensitive to packet losses while ROHC is robust against packet losses and propagation delay but does not handle out-of-order packet arrivals (19).

Pseudowire, however, can handle out-of-order arrivals by either dropping the out-of-order packets or by re-sequencing the packets into the correct order when possible. For packet loss issues, Pseudowire has a frame loss detection feature that enables the receiving end to recognize losses by tracking the sequence number of the received packets (20). Once a loss is detected, the Packet Loss Concealment (PLC) technique is applied to replace the lost bits by either substituting the lost bits with zero bits or by replicating the previous byte stream.

III. Prospective Wireless Solutions for Backhaul

With the advent of Pseudowire technologies described in the previous section, researchers are seeking innovative ways to utilize new broadband wireless solutions such as Wi-Fi and WiMAX as prospective technologies for cellular backhaul networks. In this section, we give a short overview of Wi-Fi and WiMAX wireless technologies and discuss throughput performance, distance coverage, packet efficiency, and QoS as relevant to their applicability to backhaul systems. We leave the discussion on timing and synchronization to Section IV-B.

A. Wi-Fi Network Technology

Wi-Fi was originally designed for indoor usage based on the IEEE 802.11 standards and operates in the 5 GHz and 2.4 GHz unlicensed bands. Recent research advances in industry and academia demonstrated the feasibility of long distance Wi-Fi connectivity up to 38 km (21–23). As such, Wi-Fi can be an attractive low cost solution for backhaul which can substitute microwave links. As shown in Figure 5, Wi-Fi links can be used in combination with Pseudowire to backhaul traffic from nearby cell sites to the radio network controller residing in the core network. A base station may have a Wi-Fi interface with built-in Pseudowire capabilities as in site "B" and can

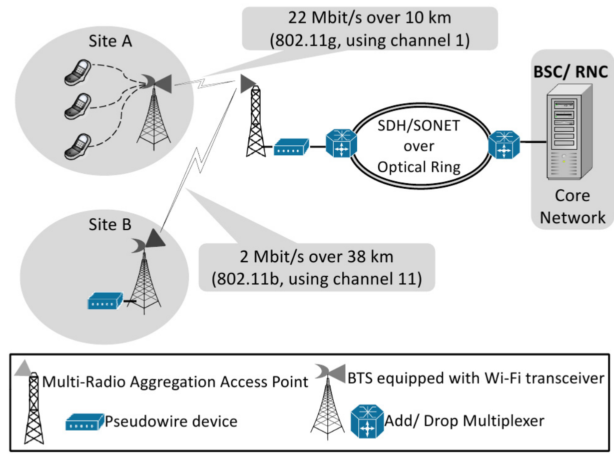


Fig. 5. Wi-Fi Backhaul Network

directly backhaul its traffic back to the nearest aggregation access point or an additional unit as in site "A". Notice that in our example, site "A" and site "B" use non-overlapping Wi-Fi channels (e.g., channel 1 and channel 11) to interact with the multi-radio aggregation access point to avoid collisions. Although Wi-Fi technology offers attractive cost benefits and deployment flexibility for backhaul networks, it poses design issues relevant to the achieved throughput, distance coverage, packet overhead, and timing and synchronization.

Relevant to throughput, several Wi-Fi router manufacturers such as (24), have added proprietary extensions to their 802.11 products, to support up to 108 Mbit/s. In addition, the new IEEE 802.11n standard significantly improves the network throughput of up to 600 Mbit/s by using Multiple Input Multiple Output (MIMO) technologies, which use multiple antennas at both transmitter and receiver. A comprehensive literature survey of MIMO techniques can be found in (25). The Spatial Reuse TDMA (STDMA) technique (26; 27) was proposed in (21) to increase the capacity of Wi-Fi by scheduling links for various simultaneous transmissions. The idea behind STDMA is that when wireless nodes are spread out geographically, then the same time slot can be used for concurrent transmissions between nodes with sufficient spatial separation (27; 28). In addition, traditional frequency planning is required to enhance the network capacity, where using multiple non-overlapping channels allows simultaneous communications between nodes without interference (29–31). Finally, frequency reuse techniques can be used such that the same Wi-Fi channels are used in sufficiently separated communicating groups. Therefore the throughput achieved in Wi-Fi networks offers a potential solution to aggregate backhaul connections from a number of base station sites back to the core network at a low cost.

As Wi-Fi was originally designed for indoor usage, using it for point-to-point long-distance links, which is relevant to backhaul, was an active area of experimental research in the past few years. In (21; 22), the authors built a testbed in a rural setting and demonstrated that a 38 km long link (802.11b) is feasible using highly directional antennas (23-dBi parabolic grid antenna placed on top of a 40 m tower). In addition, several industrial vendors (e.g. (23)), offer 802.11 commercial products to provide long distance outdoor coverage, albeit with proprietary modification of the 802.11 MAC protocol. For example, in (23), long distance 802.11g is offered with throughput up to 22 Mbit/s over 10 km in Orthogonal Frequency Division Multiplexing (OFDM) mode, and approximately 40 km in Direct Sequence Spread Spectrum (DSSS) mode at lower rates.

The usage of long distance Wi-Fi connections, however, raises several technical challenges in both the physical and MAC layers. Specifically, in the *physical layer*, 802.11b uses the DSSS modulation techniques where transmission is spread over a large bandwidth and is hence susceptible to multipath fading (21). In OFDM mode, on the other hand, multiple narrow channels are used to transmit data, where each channel is modulated with a low data rate sub-carrier, and the sum from all channels yields a high data rate. OFDM sub-carriers have a long symbol duration; hence multi-path problems are avoided as long as the delay spread is below the symbol duration. At *the MAC layer*, many parameter values are not suitable for outdoor scenarios, e.g., acknowledgement timeout, Contention Window (CW) and round-trip time. This is because in 802.11 MAC, Acknowledgement (ACK) packets must be sent to ensure successful delivery. The default ACK timeout value of 20 μs is too short for long distance links (the propagation delay over 15 km is 50 μs) (21). Nevertheless, the achieved distances of 10 km and 40 km carry potential to backhaul nearby sites at low cost as well as decently distant sites in suburban environments.

Wi-Fi packet efficiency comes into play when using Wi-Fi to backhaul voice traffic. To illustrate this issue, let us use the same EVRC codec VoIP example, which offers VoIP payload sizes of 24 bytes. We assume that ROHC header compression techniques are used to reduce RTP/UDP/IP headers size from 40 bytes to 1 byte leading to VoIP packet size of 25 bytes. The Wi-Fi MAC frame format including frame control, duration ID, addresses, sequence control, data and Frame Check Sequence (FCS) fields adds 28 bytes to the payload resulting in 53% MAC overhead. Notice that Wi-Fi PHY layer with PLCP preamble and header leads to another 24 bytes of overhead. To address this issue and enhance the efficiency, concatenation techniques are introduced in (32) which encapsulate multiple voice payloads into one PHY frame with one MAC header. Therefore, concatenation techniques as well as header compression techniques should be considered in backhaul applications.

To support the required QoS in a backhaul application, Wi-Fi must be deployed beyond the standard configurations (e.g,. 802.11b, 802.11g) which rely on the Distributed Coordination Function (DCF) MAC protocol for channel access[5]. Since DCF does not support QoS, the IEEE 802.11e amendment was introduced to support QoS in Wi-Fi networks. In this regard, there are two methods for channel access: Hybrid coordination function Controlled Channel Access (HCCA) and Enhanced Distributed Channel Access (EDCA). HCCA is a centralized contention scheme and EDCA is a distributed priority based contention scheme. In the latter, each node assigns high priority traffic (e.g., VoIP) shorter backoff times than best effort traffic. Both schemes have traffic differentiation features. However, HCCA support is not mandatory in 802.11e AP and only few APs have currently enabled this feature. Relevant to backhaul networks, the fact that HCCA is not widely deployed and that EDCA does not support guaranteed QoS. It necessitates careful design especially when the Wi-Fi network is used to support residential broadband connectivity in addition to cellular backhaul traffic.

[5]Point Coordination Function (PCF) was proposed in infrastructure mode for centralized contention control, however, only a few Access Point (AP)s have enabled this feature in practice.

B. WiMAX Network Technology

WiMAX was originally designed for outdoor usage and is defined in the IEEE 802.16 standards for broadband wireless technologies. WiMAX is based on OFDM and provides higher throughput and longer coverage range compared to Wi-Fi. It can operate in both unlicensed (typically 2.4 GHz and 5.8 GHz) and licensed (typically 700 MHz, 2.3 GHz, 2.5 GHz, and 3.5 GHz) bands. Using unlicensed bands, it can reduce the CAPEX at the cost of interference problems. Compared to microwave, WiMAX is less costly in terms of licensed spectrum fees (33). In addition, WiMAX can operate in non-LOS scenarios while microwave has strict LOS requirements. Backhaul applications can use the relatively simple 802.16-2004 standard for fixed connectivity applications, in point-to-point, point-to-multipoint, and mesh topologies.

WiMAX supports relatively high data throughput. Theoretically, WiMAX can provide single channel data rates up to 75 Mbit/s and up to 350 Mbit/s via multiple channel aggregation (34). WiMAX can operate in various frequency bands which has effects on the bandwidth capacity and the distance coverage. The higher the frequency, the greater the bandwidth capacity and the shorter the coverage range. MIMO and Adaptive Antenna Steering (AAS) can be used to enhance WiMAX throughput. In addition, WiMAX supports bandwidth management via centralized bandwidth scheduling in both uplink and downlink directions. This allows efficient resource allocation and hence higher achieved capacities (35). Using orthogonal frequency division multiple access (OFDMA) concepts (a.k.a., sub-channelization), multiple subscriber stations can communicate with the base station in the same timeslot over separate subchannels without interfering with each other (36). Recent WiMAX backhaul products such as in (37) can be deployed as point-to-multipoint base stations with 6 sectors with each sector supporting a throughput of 6 E1 links.

WiMAX supports a maximum range of approximately 50 km for single-hop architectures in the presence of line of sight and 25 km in non-line of sight connectivity scenarios (37). High-gain directional antennas can be used to significantly increase range and throughput. Packet overhead can be analyzed similar to Wi-Fi. The MAC Protocol Data Unit (PDU) overhead of WiMAX is 6 bytes (33; 38). Hence, when using WiMAX to backhaul voice traffic, the backhaul voice overhead ratio becomes 19% (6 / (25+6)) which is much more efficient than Wi-Fi. This MAC overhead ratio can be reduced by concatenating multiple Service Data Unit (SDU)s for the same service into a single MAC PDU (33). On the other hand, the PHY header of WiMAX depends on various parameters such

TABLE II
BASE STATION SYNCHRONIZATION REQUIREMENTS IN MOBILE WIRELESS NETWORKS

Wireless Technologies	**Technical Specification**	**Frequency Accuracy (parts per billion: ppb)**	**Timing Accuracy**
GSM	3GPP TS 45.010	50	N/A
UMTS/WCDMA (FDD)	3GPP TS 25.104	50	N/A
UMTS/WCDMA (TDD)	3GPP TS 25.105, 3GPP TS 25.402	50	2.5 μs
CDMA2000	3GPP2 C.S0010-B,3GPP2 C.S0002-B	50	1 μs GPS

as channel bandwidth, symbol time duration and coding rate. In (39), the PHY overhead of WiMAX was analyzed and it was shown that WiMAX has a high PHY overhead ratio (more than 50 %) (39). With the same concatenation techniques, multiple MAC PDUs can be put together into a single burst to save PHY bandwidth (33). Higher packing efficiency is indeed desirable for backhaul networks as it allows supporting more E1/T1 connections per WiMAX link. However, for both Wi-Fi and WiMAX networks, concatenation should also be performed such that it does not cause high jitter to delay sensitive traffic as well as to timing synchronization operation.

Unlike standard Wi-Fi, WiMAX PMP mode can support guaranteed QoS through centralized scheduling mechanisms for different service classes (38). In WiMAX 802.16-2004 standard, four QoS classes were defined including Unsolicited Granted Service (UGS), Real Time Polling Service (rtPS), Non Real Time Polling Service (nrtPS) and best effort. A UGS connection communicates its traffic rate requirements to the base station during connection establishment and the base station allocates exactly such amount of bandwidth in each frame whether it is used or not. This is similar to circuit switched T1/E1 concept. rtPS uses dedicated periodic slots in the uplink channel for sending bandwidth requests to the base station; nrtPS connections use dedicated periodic request slots, but the allocation of dedicated requests is much longer than rtPS connections. nrtPS connections may use contention-based time slots to send their requests to the base station. These contention slots are also used by the best effort connections.

IV. Timing and Synchronization Aspect

This section discusses the fundamental challenge in wireless backhaul relevant to timing and synchronization. Current cellular systems need frequency and time synchronization for proper operation. In our context, frequency synchronization means that all local clocks at base station sites as well as radio network controllers are locked to a common highly accurate frequency reference. On the other hand, time synchronization refers to the establishment of a common time reference among network nodes which ensures that base station clocks are in phase. For instance, requiring that two watches be frequency synchronized means that they should tick at the same speed irrespective whether they show the same time (e.g., one clock may show 8:00 and the other may show 9:00). The clocks are said to be time synchronized only when they both display the same time (e.g., both show 8:00). Obviously, time synchronization requires frequency synchronization. Table II summarizes frequency and time accuracy requirements in traditional 2G and 3G systems. More details on the requirements for other cellular systems can be found in (40).

Frequency accuracy is always required in cellular systems to discipline base station local clocks and hence maintain the accuracy of the radio carrier frequency on the airlink. Misaligned radio carriers can result in undesirable interference in the cellular network as well as violations of the allotted bandwidth (41). Frequency synchronization is also required throughout the network in some systems such as GSM for smooth handover in order to prevent call dropping and speech clipping problems. This is because during the handoff preparation phase, while a connection with the target base station is being made, agreement with the target base station on new frequency and timing offsets is required. The agreement process is much shorter (i.e., below 100 ms) when the current and target base stations are synchronized to the same frequency reference and hence leading to reduced handoff duration (42). This aspect was confirmed in the experimental study in (43), where it was shown that if two BTSs have a frequency offset greater than 100 part per billion (ppb), calls which successfully complete handovers entail a poor Mean Opinion Score (MOS) value and high percentage of speech clipping. The results also indicated call dropping and degraded quality as a result of the longer handoff duration due to the long synchronization/agreement time with the target base station.

On the other hand, *timing accuracy* is needed in cases where base stations require an accurate time reference, such as in the Time Division Duplex (TDD) mode for UMTS which timing alignment is critical to ensure minimal interference in the network between base stations. Timing synchronization is also important to the operation of some systems like CDMA2000 which derives all time critical CDMA transmissions and operations such as pilot channels, pseudo noise sequences and Walsh functions from a highly accurate time reference e.g. GPS. Furthermore, some positioning services (e.g., time of arrival, assisted GPS) depend on the presence of a common time reference in all base stations to locate the user based on the observed propagation delays from multiple base stations. Finally, timing synchronization is also needed in soft handoff scenarios in which a mobile can communicate simultaneously with multiple base stations. This guarantees that minimal soft combining buffers are required by the mobile device as all frames from all base stations in the mobile's active set arrive at similar times, and ensures that cross interference management mechanisms between base stations operate properly (44).

A. Timing and Synchronization in Circuit Switched Networks

In TDM circuit switched networks, synchronization is an important design objective. If the transmitter and the receiver are not synchronized, bit slipping problems may occur. For

TABLE III
A SET OF FOUR ITU-T RECOMMENDATIONS ON TIMING AND SYNCHRONIZATION OVER PACKET SWITCHED NETWORKS

Standard - Series	Description
G.8261	• Defines the ways to deploy synchronization over packet switched networks • Sepcifies aspects of synchronization in packet swithced (e.g. the maximum network limits of jitter and wander)
G.8262	• Outlines requirements for timing devices used to support synchronization in Synchronous Ethernet, called Ethernet Equipment Clock (EEC)
G.8263	• Addresses the specification of the packet based clocks
G.8264	• Specifies the requirements on Ethernet transport networks in timing aspects • Details the timing architecture as well as describes how and where time and timing will flow through the architecture

example, if the receiver's clock is slower than the clock on the transmitter's side for 1 part per million (ppm), the transmitter sent 1,000,000 bits but the output from the receiver is 999,999 bits (42). This problem exacerbates with increased data rates, such as in SDH/SONET systems. In these systems, to maintain timing synchronization, a hierarchical master/slave clock system is usually implemented, where the master clock, with very high accuracy (10^{-11}), provides timing information to slave clocks which they use to derive their timing. This means that the master clock incurs one slip every 10^{11} ticks when compared to the ideal clock.

The ITU Recommendation G.811 suggests a four level clock hierarchy (42; 45). Assume that we have three cascaded digital switching exchanges with the master clock connected to the first exchange and customer equipment with a slave clock connected to the last. In this system, the clock of the first exchange is synchronized by the master clock while slave clocks residing in the other exchanges[6] synchronize their rates to the timing of the received signal using digital phased locked loops (DPLL). The process continues until the end device. Notice that the quality of the slave clock's accuracy degrades as recovered timing depends on the DPLL and its jitter bandwidth (which is very narrow). In our example, since the second exchange's clock was not directly synchronized by the master clock, it is referred to as stratum 2 clock. Similarly, since the clock in the third exchange is synchronized by a signal synchronized to the stratum 2 clock in the second exchange, it is referred to as stratum 3 clock. The customer device has a stratum 4 clock. Thus, the clocks in the network are said to be traceable to the primary reference clock. Reference (46) provides a thorough survey of the historical evolution of synchronization systems including PDH, SDH/SONET, and ATM.

The main timing measures for traffic interfaces in TDM networks are jitter, wander and bit slip limits (47). ITU-T Rec. G.823 and G.824 define the requirements for jitter and wander at synchronization interfaces based on the E1 and T1 respectively (48; 49). In addition, ITU-T Rec. G.822 specifies the applicable slip rate objectives. When the clock of the transmitting equipment is different from the clock recovered at the receiving end, the slip buffer is needed (50).

[6]In many cases, a stand alone office clock is enslaved to the master clock received from the TDM network which in turn synchronizes the recovered clock signals to the local exchanges clocks (46).

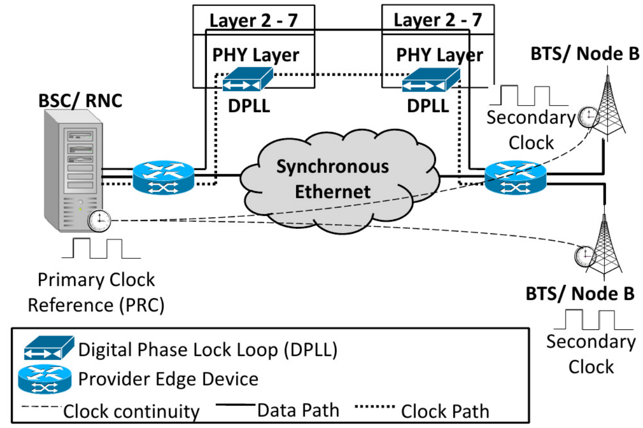


Fig. 6. Synchronous Ethernet Concept

B. *Timing and Synchronization in Packet Switched Networks*

The traditional packet switched networks do not need synchronization to operate and hence provide no timing synchronization services. In order to allow timing distribution over emulated circuits, new techniques and protocols were proposed to distribute reference timing signal. In packet networks, clocks can be recovered using adaptive and differential methods (47). Adaptive methods keep track of the inter-arrival time of timing packets or make observations to the arrival buffer levels to maintain time and frequency synchronization. In differential methods, we consider the fact that sometimes packet switched networks may have different primary clock reference from the carried TDM service clock. In this case, the difference between both clocks is encoded into the timing packet stream at the sending packet network edge and recovered at the receiving edge. When the primary clock reference is distributed and is made available to both ends (i.e., at the core network and the base station sites such as in the case of GPS), there is no need to recover timing.

Table III summarizes the related ITU-T Recommendations on Timing and Synchronization. According to (47), there are two primary methods for reference timing signal distribution: Plesiochronous and network synchronous methods (e.g. Synchronous Ethernet) and packet-based methods (e.g. NTP, IEEE 1588 PTP). We next describe the Synchronous Ethernet and the packet-based methods in more details.

1) Synchronous Ethernet is a technique recently proposed to distribute timing signal using a synchronous physical layer, in a similar fashion to TDM networks. In Synchronous Ethernet, each node recovers the clock information from the upstream node, filters jitter and wander via DPLL and then distributes to downstream nodes via physical layer regardless of the higher layer transmission protocols (see Figure 6). While conventional Ethernet relies on the reference frequency provided by the free-running operation of the local oscillator

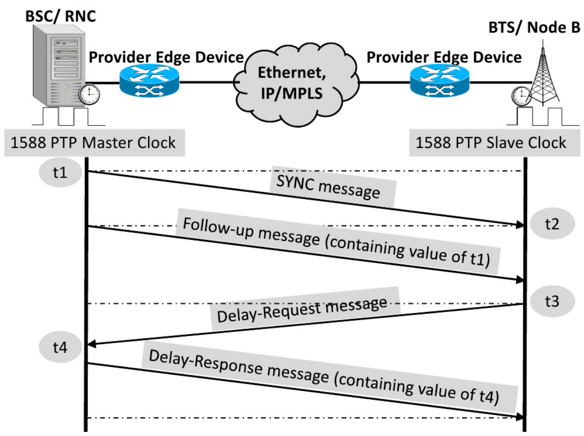


Fig. 7. IEEE 1588 Exchange Messages

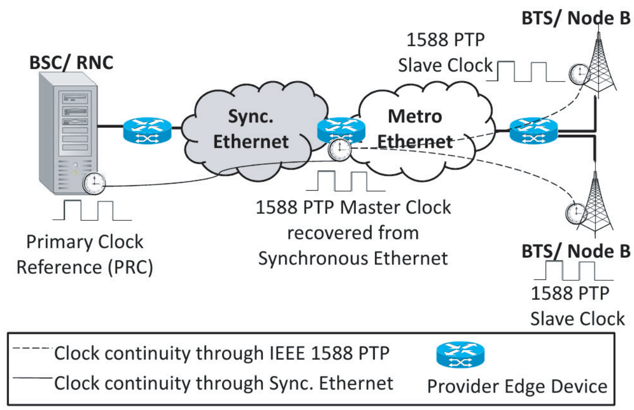


Fig. 8. IEEE 1588 and Synchronous Ethernet

on the order of 100 ppm (i.e., 10^{-4}) (47), with synchronous Ethernet, highly accurate and stable frequency is distributed at the physical layer without impacting the Ethernet operation. The advantage of distributing a physical layer clock is that the timing performance would not be affected by the impairments from the higher network layers, i.e., packet loss and packet delay variations (51; 52). Synchronous Ethernet can satisfy the requirements of cellular networks timing accuracy as it was shown to achieve $<$ 2 ppb accuracy in (51; 52). However, using Synchronous Ethernet poses a hard end-to-end connectivity requirement between base stations and the radio controller to guarantee the traceability to a single master clock. Consequently, network switches need to be upgraded to support Synchronous Ethernet. In addition, it is still a challenge when crossing multiple operator domains or having to reach the base stations through non-synchronous networks. In such scenarios, packet based synchronization methods, (e.g., IEEE 1588 PTP), can be deployed to extend timing information to the end nodes (53).

2) The packet-based methods rely on timing information carried by the packets (e.g. sending dedicated timestamp messages or two-way timing information transfer) (47). Timing packets are not necessarily coupled with data packet streams and are usually sent on a separate stream with their own QoS rules. The protocols used for packet network synchronization are Network Time Protocol (NTP) and IEEE 1588 Precision Time Protocol (PTP). The NTP protocol (RFC 1305) uses software-based implementation for synchronization; that leads to inaccurate estimation of timing information (54). In fact, the currently deployed NTP (RFC 4330: NTPv4) delivers timing accuracy on the order of 10 ms which is not adequate for the accuracy requirements in cellular networks. IEEE 1588 PTP protocol addresses this shortcoming of NTP and provides more precise timing information by utilizing hardware-based schemes to accurately timestamp packets departure times instead of software-based methods which are susceptible to delay variations (54). PTP was shown to achieve frequency accuracy below the required 50 ppb as discussed in (51; 52).

The IEEE 1588 PTP uses master/slave synchronization paradigm (see Figure 7). The master clock sends a message to its slaves to initiate the synchronization via multicast transmission; then each slave accomplishes the synchronization by responding to the master. The synchronization process can be divided into two phases. First, the master sends a SYNC message to slave clocks; which receive the master's SYNC message and note the packet arrival time (t2). Then the master sends a follow-up message containing a more accurate timestamp which carries the actual time at which the SYNC message departed the master clock's interface (t1). Now the slave clocks know master-slave difference D_{ms}, which corresponds to the clocks offset (O) plus master-slave propagation delay, P_{ms}. In the second phase, the slave clock sends a delay request message to the master (t3), then the master timestamps the received message and sends it back to the slave via a delay response message (t4). Now the slave knows slave-master difference, D_{sm}, which corresponds to the offset (O) plus slave-master propagation delay P_{sm}. If the ratio R denotes the ratio $\frac{P_{sm}}{P_{ms}}$, then it can be shown that the propagation delay from the master to the slave clocks is given as $P_{ms} = \frac{D_{ms}+D_{sm}}{1+R}$. The clocks offset O is given as $O = D_{ms} - P_{ms}$ and the propagation delay from the slave to the master $P_{sm} = RP_{ms}$. When the link between the master and slave clocks is symmetric, then $R = 1$, otherwise such as in the case of DSL links then the ratio R can be estimated by observing packet inter-arrival time dispersion (see (55)).

The "IEEE 1588 version 2" has more features than the originally released "version 1", including the addition of a unicast transmission feature and an increased message rate. This is because in the multicast model, the client has to listen to all the delay-request and delay-response messages produced by or for other clients. This poses unnecessary load on the client. To minimize the clients' load, deploying multicast only for SYNC messages and using unicast in the delay adjust phase may be more appropriate (56; 57). Furthermore, the increased message rate reduces the impact of packet losses and improves the accuracy resolution (56; 57).

Packet based methods, such as IEEE 1588 can be combined with Synchronous Ethernet to circumvent its end-to-end connectivity requirement and allow traversing multiple domains. As shown in Figure 8, the RNC in the core network connects to the base station sites via a Pseudowire connection over two cascaded domains: Synchronous Ethernet followed by Metro Ethernet. Since the RNC synchronized output bit stream is first sent over the Synchronous Ethernet, the physical layer

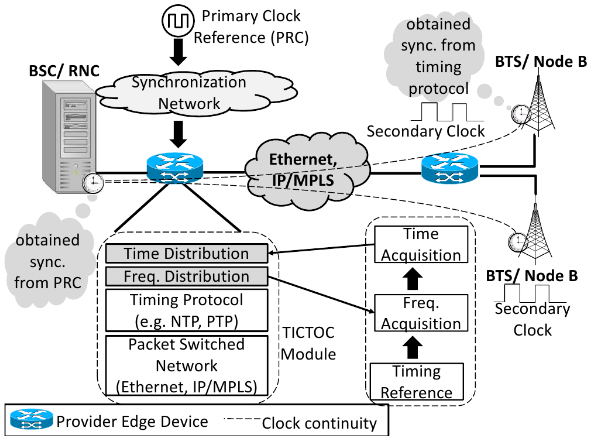


Fig. 9. TICTOC Network Model, adapted from (58)

clocks are traceable to the same master clock. At the edge of the Metro Ethernet network, timing is conveyed using PTP protocol messaging. At the provider edge, TDM service clocks are regenerated and conveyed to the base stations.

Finally, we conclude this subsection by drawing the reader's attention that there has been a recent effort in the IETF under the Timing over IP Connections and Transmission of Clock (TICTOC) working group to propose a unified framework for frequency and timing distribution over packet switched networks. This standard draft (58), points out the shortcomings of the existing synchronization solutions and also outlines a complete and robust time and frequency transfer system in packet switched networks (58). The TICTOC architecture is based on frequency distribution and time distribution layers carried over the network by the timing protocol, e.g., NTP, IEEE 1588 PTP (see Figure 9). The slave clocks derive the frequency accuracy from the master clock through a frequency distribution protocol. Then, if the application requires time accuracy, the time acquisition module uses an accurate frequency reference from the frequency layer and begins the master-slave timestamp procedure (e.g., using IEEE 1588) (58).

C. Timing and Synchronization in Wi-Fi and WiMAX Networks

The IEEE 802.11 standard defines a simple protocol for clock synchronization (59) which depends on whether Wi-Fi nodes communicate in the infrastructure or ad hoc mode. In the infrastructure mode, Wi-Fi nodes communicate through an access point (AP), whereas in the ad hoc mode, nodes can communicate directly, i.e, without an AP. When operating in the infrastructure mode, a master/slave clock synchronization mechanism is implemented where the AP acts as a master. The AP periodically transmits the beacon frame that includes timestamp information to which all of the slaves' clocks have to synchronize (60). On the other hand, when operating in the ad hoc mode, synchronization is more complicated because all nodes must participate in the beacon generation process (61; 62). In this regard, each node chooses a random delay before it attempts to transmit a beacon. If it receives a beacon frame from another node before the delay expires, it does not transmit anything but simply adjusts its own clock to the timing information from the received beacon frame. In the case that the delay period finishes without hearing anything from its neighbors, the node will transmit its beacon frame to which the receiving nodes have to synchronize their clocks according to the timestamp in the beacon (61; 62). Through this process, the network-wide synchronization can be achieved. In (63), an implementation of IEEE 1588 PTP over Wi-Fi network was introduced in the ad hoc mode to provide more accurate timing reference. The results, however, are only applicable to the accuracy level for instrumentation applications. Timing and synchronization for cellular applications needs further research while GPS based synchronization can be used in the meantime.

WiMAX network needs synchronization in both TDD and Frequency Division Duplex (FDD) modes. For example, in WiMAX TDD frame structure, the Transmit/Receive Transition Gap (TTG) and Receive/Transmit Transition Gap (RTG) define the guard band time gaps. The base station needs to keep clock synchronization accurate to prevent TDD frame drifts outside the guard bands and interferes with adjacent frames. The less accurate the clock source, the wider the required guard bands (64). Timing and synchronization among adjacent base stations is needed to minimize interference. The IEEE 802.16 standard defines the use of GPS for timing synchronization (38). In practice, the IEEE 1588 PTP may be used as an alternative due to its lower cost. For highly reliable synchronization in the network, IEEE 1588 PTP can serve as a backup timing reference in base stations deployed with GPS receivers. If the GPS signal becomes unavailable, the base station can still perform synchronization using IEEE 1588 PTP (64).

V. COMPARISON, TRENDS AND OPEN ISSUES

In this section, we start by summarizing and comparing all backhaul technologies discussed in the previous sections. We then address relevant future trends such as wireless mesh backhaul, and "All-IP" network designs including femtocells.

A. Comparison Among Different Backhaul Technologies

From Table IV, we can see that deploying leased T1/E1 copper provides suitable support for 2G GSM backhaul due to its guaranteed QoS and timing reference. However, for the UMTS 3G system which needs to support both voice and high speed data traffic, leased T1/E1 copper becomes a cost-inefficient choice because the price increases linearly with capacity. On the other hand, optical fiber transmission technologies offer high capacity which is sufficient for 3G and 4G cellular technologies. It can also guarantee QoS and provide timing reference; however, this comes at cost of high installation and maintenance fees. Packet switched networks (e.g., Ethernet and IP) offer high capacity (depending on the medium) at significantly low cost. However, they incur low packet efficiency when carrying voice payloads, and do not natively support QoS and timing synchronization.

On the other hand, deploying wireless backhaul relaxes the requirements of the availability of wired connections and their infrastructure installations. Microwave technologies which usually use synchronous transmission techniques (e.g., SDH or nxT1/E1) can guarantee QoS, and provide timing

TABLE IV
BACKHAUL TECHNOLOGY COMPARISON

Technology	Capacity	Distance Coverage	QoS	Timing and Synchronization	Cost
Leased T1/E1 Copper	Low [T1=1.544 Mbit/s E1=2.048 Mbit/s]	No additional requirement	Guarantees QoS	Provides timing and synchronization	Low CAPEX (Already exists); High OPEX (Ongoing high leasing cost); Cost increases linearly with capacity and is proportional to distance
Optical Fiber	High [STS-1 = 51.84 Mbit/s STS-3c = 155.52 Mbit/s]	No additional requirement	Guarantees QoS	Provides timing and synchronization	High installation cost; Cost is proportional to distance
Ethernet/ IP	High [10/100/1000 Mbit/s]	No additional requirement	QoS normally not supported	Lack of timing and synchronization	Cost efficient
Microwave	High (2 Mbit/s-170 Mbit/s)	LOS requirement	Guarantees QoS	Provides timing and synchronization	Upfront high CAPEX; Licensed spectrum fee; High maintenance cost;
Satellite	Medium (384 kbit/s - 4.09 Mbit/s)	Extremely flexible coverage	Propagation delay problem	Provides timing and synchronization	Much more expensive compared to other choices
Wi-Fi	High [11 Mbit/s (802.11b) 54 Mbit/s (802.11g) 600 Mbit/s (802.11n)]	LOS requirement; Supports multihop for longer distance	802.11e EDCA provides service classes but cannot guarantee QoS	Has simple mechanism to provide timing and synchronization but the accuracy level is insufficient for backhaul applications	Low cost due to mass production and unlicensed spectrum
WiMAX	High [75 Mbit/s (single channel) 350 Mbit/s, multi-channel]	Supports LOS and non-LOS; Supports multihop for longer distance	Supports guaranteed QoS in PMP mode	The standard defined using GPS as a reference clock for network synchronization	Licensed spectrum fee; Cost is expected to decrease due to standardization

synchronization. It can offer data rates ranging from 2 - 170 Mbit/s depending on the framing protocol and the modulation techniques. However, this radio link requires LOS for communications and poses high upfront CAPEX, in terms of costly equipment and licensed spectrum fees. Satellite backhaul offers a solution for challenging areas where no other technologies can be implemented. It has a flexible coverage range and provides timing reference but suffers from propagation delay and high costs compared to other methods.

Wi-Fi and WiMAX are emerging as prospective wireless backhaul technologies due to their high throughput and long distance coverage. However, Wi-Fi suffers from several disadvantages such as low packet efficiency, lack of QoS guarantees, and the lack of accurate synchronization mechanisms which match the backhaul applications requirements. On the other hand, WiMAX has many features that outperform Wi-Fi. For example, it can guarantee QoS and provide more accurate network synchronization, compared to rudimentary synchronization mechanisms in Wi-Fi. The 802.16-2004 standard uses positioning services (e.g., GPS) for network synchronization and Wi-Fi backhaul may use GPS as a viable workaround. However, implementing IEEE 1588 PTP over WiMAX and Wi-Fi for cost efficiency or as a backup timing reference in base stations deployed with GPS receivers is still an active area of research. Although WiMAX has a licensed spectrum fee, the standardization is expected to drive the total cost down. Nevertheless, Wi-Fi offers very low cost due to mass production and unlicensed spectrum usage.

B. Wireless Mesh Backhaul

Multihop Wi-Fi and WiMAX, or *wireless mesh* networks, offer several advantages such as longer distance coverage and higher throughput over long distances. For instance, traffic can be routed around obstacles in non-LOS environments and hence effectively reduces the distance between transceivers at the base stations and transceivers at the aggregation points using mesh nodes. This can increase the network throughput due to lower path loss and spatial reuse. In dense urban environments where microcells/ picocells are deployed, wireless mesh backhaul can offer significant cost savings by connecting multiple microcells and forwarding their traffic to a single wired location (4).

Wireless mesh backhaul, however, poses challenges in areas such as security, billing, resource reservation, QoS, and timing and synchronization (65–68). Relevant security challenges include network availability, confidentiality, integrity, and authenticity with goals to enable secure routing, intrusion detection, and facilitate trust and key management (66). Billing models and accounting mechanisms are required when a wireless mesh network is administered by third parties. In (67), the authors offer a bandwidth management and accounting mechanism that allows the base stations or radio network controllers to dynamically claim and release bandwidth from the mesh network depending on the observed network load. The reservation for resources can be performed according to standard mechanisms as in (69). Let us now briefly highlight aspects of multihop Wi-Fi and WiMAX technologies and discuss their QoS and synchronization challenges.

1) Wi-Fi mesh backhaul: Wi-Fi mesh backhaul can cover longer distance, such as 80 km over a three hop Wi-Fi link (a max of 38 km for a single Wi-Fi link as demonstrated in (21)). In (70), the surveys of existing proposed methods to enhance the channel utilization in Wi-Fi mesh are presented. Product vendors such as (4) have been offering proprietary Wi-Fi mesh for mobile operators' backhaul. For example, (4) announced a wireless mesh backhaul solution for mobile operators which supports a capacity up to eight T1s or six E1s over as many as five wireless hops. The IEEE standardization bodies also contributed to the development of Wi-Fi mesh networks by proposing the 802.11s standard (71). 802.11s addresses the current shortcomings of IEEE 802.11 MAC protocol in multihop environments, such as hidden and exposed terminals and unfairness problems (72; 73). It also defines the Mesh Deterministic Access (MDA) as an optional MAC scheme which introduces a medium reservation for QoS (74). However, MDA behaves similarly to EDCA for Wi-Fi single hops and cannot guarantee QoS. Achieving guaranteed QoS is a subject of ongoing research; for instance using RSVP-like techniques such as in (68; 75). On the other hand, synchronization in IEEE 802.11s standard is performed on a per-neighbor basis instead of the more optimal global synchronization used in standard Wi-Fi networks as it may take a long time.

2) WiMAX mesh backhaul: Similar to Wi-Fi mesh, WiMAX mesh can cover longer distance via multiple hops (76). The WiMAX 802.16-2004 standard for fixed and nomadic access can be used for cellular backhaul applications since nodes are fixed. In addition, this standard supports both PMP and mesh topologies[7]. WiMAX mesh mode includes scheduling mechanisms for data transmission between the communicating nodes. This can be achieved by using a centralized scheduling, distributed scheduling, or a hybrid of both scheduling schemes (77). Centralized scheduling algorithms are more suitable for cellular backhaul applications because they can ensure collision-free transmission, provide better QoS support, achieve better bandwidth utilization, and avoid hidden terminal issues (78; 79). Although the standards define scheduling mechanisms, they do not define service class concepts for the mesh mode and leave details of the relationship between scheduling and the interference between mesh nodes open to designers choice and research (80–82). On the other hand, WiMAX mesh network synchronization requires a common timing source which can be provided by either GPS or IEEE 1588 PTP. An accurate clock reference allows the TDD mode to coordinate simultaneous transmissions on multiple links throughout the mesh. Similar to Wi-Fi mesh networks, timing and synchronization in WiMAX mesh is still open for further research.

C. "All-IP" Network Trends and Femtocells

Mobile operators and network providers are moving towards "all-IP" networks in which all traffic leaving future base stations is natively based on IP protocols and is carried over packet switched networks with no circuit emulation requirements (83). This concept would converge the core and access networks which would result in cost savings, and simpler management and maintenance. In addition, each base station can be served by multiple radio controllers which increases system availability. A cross product of all-IP backhaul design is the introduction of *femtocells* which are home located cellular base stations at the size of a standard Wi-Fi access point and provide connectivity to cellular users over their IP network. For instance, a HSDPA femtocell can cover users at their homes and backhaul traffic over an IP based broadband connection such as xDSL. Thus, femtocells can reduce the need for adding traditional base station towers; leading to reduce backhaul establishment cost. Let us briefly describe the protocol aspects of IP based backhaul interfaces (based on the Iub interface) and then shortly discuss aspects of femtocell technology.

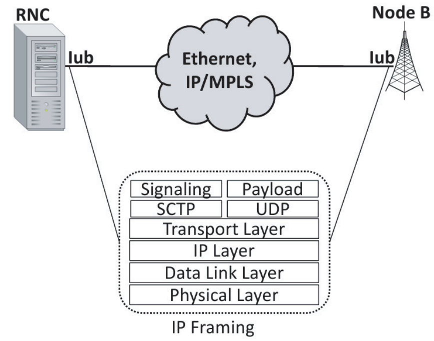


Fig. 10. IP-based Iub Interface Protocol Structure (84)

The backhaul Iub interface defines the interaction between Node Bs and RNCs (i.e., base stations and their controllers in UMTS terminology) over backhaul networks. The Iub interface protocol structure for IP-based networks is defined in (84; 85) and is shown in Figure 10. There are two types of traffic flows between RNC and Node Bs: signaling and user data. Unlike GSM Abis interface based on E1/T1 time slots or ATM deployments of Iub in UMTS networks, the IP based Iub interface is natively based on IP protocols. Signaling is carried over Stream Control Transmission Protocol (SCTP) while data is carried over UDP. UDP provides unreliable service and leaves the error checking and correction to the application layer; while SCTP provides reliable service and in-sequence transport of messages with congestion control features. This is in contrast to current AAL2 and AAL5 adaptation for data and signaling traffic in ATM based backhaul UMTS networks. As such, the use of IP based backhaul simplifies management and allows better incorporation of IP technologies for routing and QoS at the cost of more challenges in timing and synchronization.

Femtocells, also called home base stations, are low-cost base stations installed by the users for better indoor signal reception (86). These home base stations operate on low transmit power (100 mW or even 10 mW) and provide short-range coverage (20 - 30 m) (87). They share the licensed spectrum allocated to cellular service providers (in the range of 1.9 - 2.6 GHz) and offer data rates from 7.2 - 14.4 Mbit/s

[7]Recently the 802.16m superseding the 802.16j was proposed as the framework for WiMAX mesh networks.

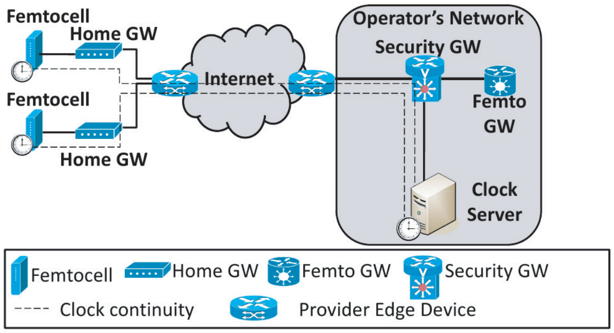


Fig. 11. A Simplified Femtocell Architecture

(87). The femtocells communicate with the cellular network over a broadband connection such as xDSL. This technology offers benefits to the users (e.g. better indoor signal reception) as well as the operators (e.g. lower operating costs).

Figure 11 shows a simplified architecture for femtocells. Femtocells connect to the operator's network over the Internet through a home gateway which includes security, firewall, and NAT functionalities. The operator's network includes a security gateway which manages Virtual Private Network (VPN) tunnels (e.g., IPSec) with the femtocells and allows access to the core network services including the PTP clock server (88). The clock server acts as a PTP master clock reference while the femtocells act as slaves. The synchronization process is based on packet-based methods as described earlier. However, deploying femtocells raises technical challenges such as interference, QoS, security, and synchronization.

Since the femtocells operate on the same frequency band as macrocells, femtocell devices may face adjacent channel interference with the macrocell. A less significant interference issue arises also due to interference among femtocells themselves when placed in close proximities (87). However, such interference can be controlled due to the low-power design of femtocells and by proper femtocell placement. In addition, when using home backhaul connection, femtocells share the backhaul bandwidth with other IP services over public IP networks. This can dramatically affect the throughput and QoS of femtocell services. It also poses security issues to the transfer of cellular channels and more importantly to the transfer of timing information. The security of the timing information is an issue as manipulating time or frequency information can cause service disruption. In addition, it is generally easier to pose denial of service attacks on femtocells than macro base stations and hence disrupts their operation. The physical security of the femtocell itself is also important as users can tamper with the femtocell hardware to create man-in-the-middle attacks which allow channel hijacking.

Finally, synchronization is a major challenge due to xDSL asymmetric bandwidth and the load on the core PTP time servers. As femtocells are likely to use xDSL, the conventional IEEE 1588 PTP may not work properly due to the symmetrical links assumption. The study in (55) shows the performance degradation of the IEEE 1588 PTP when working in asymmetrical links and proposes a mechanism to estimate the asymmetry ratio among the forward and reverse directions as we discussed in Section IV-B. According to (88), due to the projected large number of femtocells and the unicast nature of PTP signaling, significant overload may occur at the master clock in the core network. In addition, message security may result in high delay variations due to message protection mechanisms which can impair the accuracy of time estimated by IEEE 1588. Such issues are subject of further investigation.

VI. Conclusion

In this survey, we presented an overview of current issues and emerging cellular backhaul technologies and identified design and challenges for further research. By analyzing state-of-the-art technologies based on PDH and SDH/SONET digital transmission technologies in wired and wireless environments, over the Pseudowire technology and up to cellular backhaul based on Wi-Fi and WiMAX, we pointed out the incurred technical challenges including QoS, packet efficiency and timing synchronization. Due to their fundamental significance, we provided a dedicated discussion on timing and synchronization in cellular systems and explained the related mechanisms used in packet switched backhaul networks. Finally, we concluded the survey by discussing emerging "all-IP" network trends, femtocell networks, as well as issues of cellular backhaul over wireless mesh networks.

VII. Acronyms

AAL ATM Adaptation Layer
ACK Acknowledgement
AP Access Point
ATM Asynchronous Transfer Mode
CAPEX Capital Expense
CW Contention Window
DAMA Demand Assigned Multiple Access
DCF Distributed Coordination Function
DS0 Digital Signaling0
DSSS Direct Sequence Spread Spectrum
EDCA Enhanced Distributed Channel Access
EV-DO Evolution-Data Optimized
EVRC Enhanced Variable Rate Codec
FCS Frame Check Sequence
FDD Frequency Division Duplex
GPS Global Positioning System
GSM Global System for Mobile Communication
HCCA Hybrid coordination function Controlled Channel Access

LOS Line of Sight
MAC Media Access Control
MDA Mesh Deterministic Access
MIMO Multiple Input Multiple Output
MOS Mean Opinion Score
MPLS Multiprotocol Label Switching
nrtPS Non Real Time Polling Service
NTP Network Time Protocol
OFDM Orthogonal Frequency Division Multiplexing
PCF Point Coordination Function
PCM Pulse Code Modulation
PDU Protocol Data Unit
PHY Physical Layer
PLC Packet Loss Concealment
PLCP Physical Layer Convergence Protocol
PMP Point-to-Multipoint
ppm part per million
PSN Packet Switched Network
PTP Point-to-Point
QoS Quality of Service

OPEX Operating Expense
RNC Radio Network Controller
ROHC Robust Header Compression
RTG Receive/Transmit Transition Gap
RTP Real-time Transport Protocol
rtPS Real Time Polling Service
SCTP Stream Control Transmission Protocol
SDH Synchronous Digital Hierarchy
SDU Service Data Unit
SONET Synchronous Optical Networking
STDMA Spatial Reuse TDMA
STM-1 Synchronous Transport Module-1
STM-4 Synchronous Transport Module-4
STM-16 Synchronous Transport Module-16
TDD Time Division Duplex
TICTOC Timing over IP Connections and Transmission of Clock
TTG Transmit/Receive Transition Gap
UDP User Datagram Protocol
UGS Unsolicited Granted Service
UMTS Universal Mobile Telecom. System
VoIP Voice over IP
Wi-Fi Wireless Fidelity
WiMAX Worldwide Interoperability for Microwave Access

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