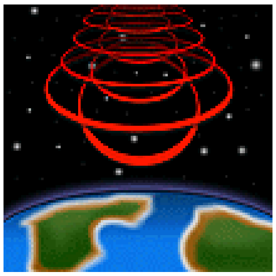
Cellular Networks: Past, Present, and Future

by *Lourens O Walters* *and* *PS Kritzinger*

Introduction



Mobile communication is the fastest growing field in the telecommunications industry. This article discusses the history, present state, and future of cellular radio networks.

Existing Mobile Communication Technologies

The cellular radio network system facilitates mobility in communication. Systems achieve mobility by transmitting data via radio waves. The following are some examples of mobile communication systems currently in use.

Paging

A simple and inexpensive form of mobile communication. An antenna or satellite broadcasts short messages to subscribers. Receivers are usually devices such as beepers, which display messages on a small screen. Transmission of data is one-way [11]. Paging systems are designed to provide reliable communication to subscribers wherever they are. This necessitates high-powered transmitters and low data rates for maximum coverage of each transmitter's designated area [7].

Communication Satellites

Satellites consist of large transponders that listen to a particular radio frequency, amplify the signal, and then rebroadcast it at another frequency. They are inherently broadcast devices. A drawback of satellites is that they have quite a large propagation delay due to the distances traveled by radio waves [11].

Cellular Radio Networks

Cellular networks are divided up into cells, each cell being serviced by one or more radio transceivers (transmitter/receiver). Communication in a cellular network is full duplex, where communication is attained by sending and receiving messages on two different frequencies - frequency division duplexing (FDD). The reason for the cellular topology of the network is to enable frequency reuse. Cells, a certain distance apart, can reuse the same frequencies, which ensures the efficient usage of limited radio resources [11].

Personal Handyphone

The Personal Handyphone System (PHS) is used in Japan. It is similar to cellular networks, however phones can also communicate directly with one another when in range. This is an advantage over cellular phones, which can only communicate with one another via base station transceivers. This system is very popular within heavily populated metropolitan areas [3].

Mobile Radio

Mobile radio is in many ways the predecessor to the cellular radio network. It is mostly analogue, and makes use of single frequencies for sending and receiving signals. Communication is half-duplex, and a button must be pressed to switch modes. They are most commonly used for emergency services, the transport sector, and the security industry [3].

History of Cellular Radio Networks

In 1946, the first car-based telephone was set up in St. Louis, Missouri, USA. The system used a single radio transmitter on top of a tall building. A single channel was used, therefore requiring a button to be pushed to talk, and released to listen [11]. This half duplex system is still used by modern day CB radio systems utilized by police and taxi operators. In the 1960s, the system was improved to a two-channel system, called the improved mobile telephone system (IMTS) [11]. Since frequencies were limited, the system could not support many users.

Cellular radio systems, implemented for the first time in the advanced mobile phone system (AMPS), support more users by allowing reuse of frequencies. AMPS is an analogue system, and is part of first generation cellular radio systems. In contrast, second generation systems are digital. In the USA, two standards are used for second generation systems: IS-95 (CDMA) and IS-136 (D-AMPS) [11, 3]. Europe consolidated to one system called the global system for mobile communications (GSM) [3]. Japan uses a system called personal digital cellular (PDC).

Present Day

Cellular radio is the fastest growing segment of the communications industry [1]. Cellular companies reported a subscription base of more than 200 million people in 1997. This figure grows by an average of 150,000 new subscribers every day [1].

Because of Europe's early commitment to one system, it is leading the field in both its subscriber base and data transmission capabilities. GSM is used in over 100 countries by over 215 operators inside and outside of Europe [3]. The Japanese PDC system is the second largest digital cellular system, followed by the IS-54/136 and IS-95 systems used in North America.

Current cellular radio systems are in their second generation (2G). The third generation of cellular systems (3G systems) will allow different systems to interoperate in order to attain global roaming across different cellular radio networks [13]. The International Telecommunication Union (ITU) has been doing research on 3G systems since the mid 1980s. Their version of a 3G system is called international mobile telecommunications - 2000 (IMT-2000).

European countries are researching 3G systems under the auspices of the European Community [13]. Their system is referred to as the universal mobile telecommunication system (UMTS), having the same goals as the IMT-2000 system. 3G systems have the following major objectives:

- Use of common global frequencies for all cellular networks.
- Worldwide roaming.

- Standardization of radio interfaces.
- High data transmission rates for both circuit and packet switched data.
- Efficient spectrum utilization schemes.

How Does it Work?

In the following explanation, a cellular telephone or any other device that can connect to a cellular radio network will be referred to as a mobile station. This is in keeping with the literature on the subject.

A cellular network consists of both land and radio based sections. Such a network is commonly referred to as a PLMN - public land mobile network [1]. The network is composed of the following entities:

- Mobile station (MS): A device used to communicate over the cellular network.
- Base station transceiver (BST): A transmitter/receiver used to transmit/receive signals over the radio interface section of the network.
- Mobile switching center (MSC): The heart of the network which sets up and maintains calls made over the network.
- Base station controller (BSC): Controls communication between a group of BSTs and a single MSC.
- Public switched telephone network (PSTN): The land based section of the network.

Figure 1 illustrates how these entities are related to one another within the network. The BSTs and their controlling BSC are often collectively referred to as the base station subsystem (BSS). As explained before, the cellular topology of the network is a result of limited radio spectrum. In order to use the radio spectrum efficiently, the same frequencies are reused in nonadjacent cells. A geographic region is divided up into cells. Each cell has a BST that transmits data via a radio link to MSs within the cell. A group of BSTs are connected to a BSC. A group of BSCs are in turn connected to a mobile switching center via microwave links or telephone lines. The MSC connects to the public switched telephone network, which switches calls to other mobile stations or land based telephones.

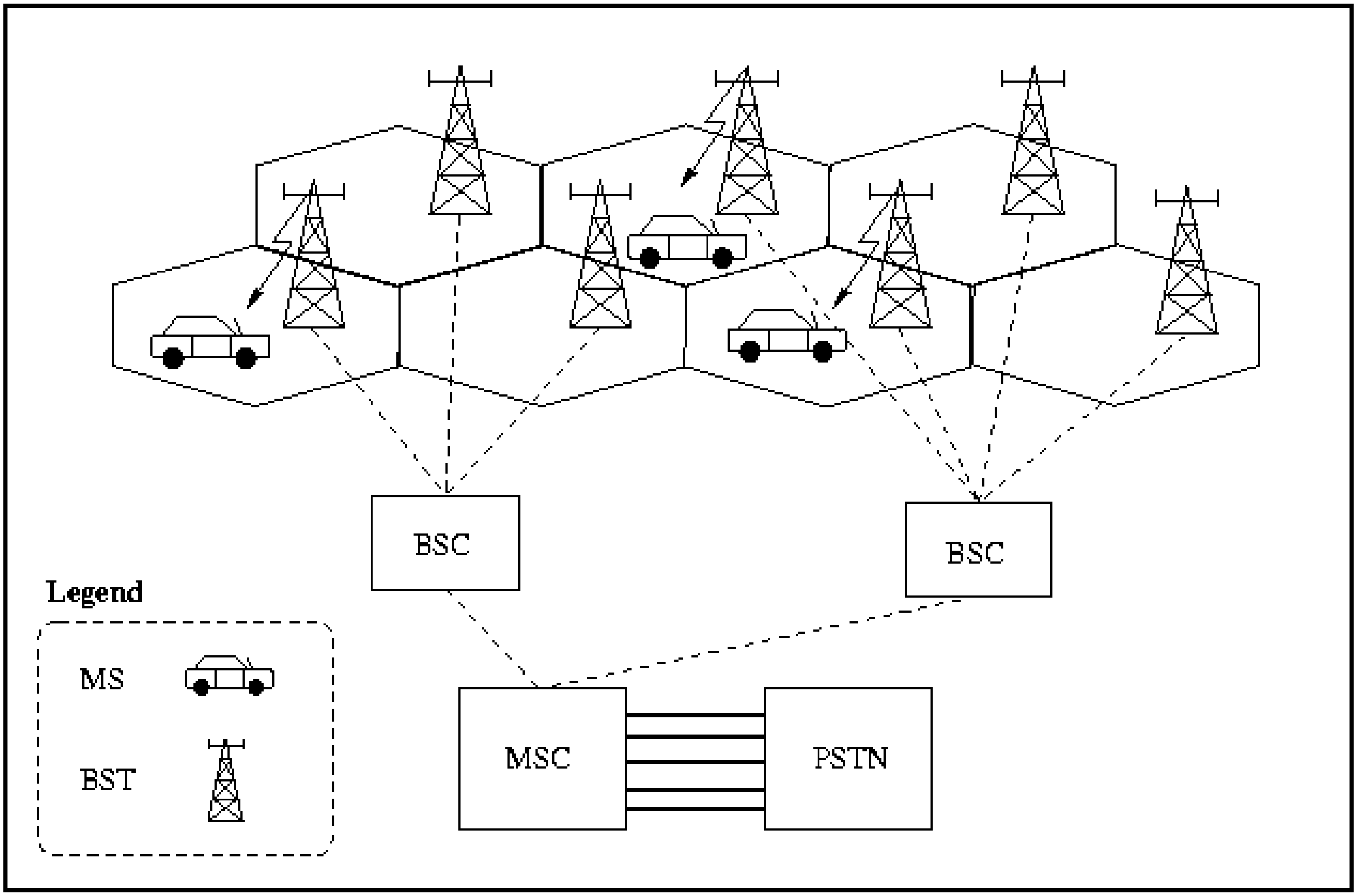


Figure 1:A cellular system

The following description of one mobile station placing a call to another mobile station best explains the underlying technology of a cellular network system.

A mobile station places a call by sending a call initiation request to its nearest base station. This request is sent on a special channel, the reverse control channel (RCC). The base station sends the request, which contains the telephone number of the called party, to the MSC. The MSC validates the request and uses the number to make a connection to the called party via the PSTN. It first connects itself to the MSC of the called party, then the MSC instructs the base station and mobile station that placed the call to switch to voice channels. The mobile station that placed the call is then connected to the called station, using unused forward and backward voice channels (FVC, BVC) [7].

The steps that take place when a mobile station receives an incoming call are as follows:

Mobile stations continually scan the forward control channel (FCC) for paging signals from base stations. When a MSC receives a request for a connection to a mobile station in its area, it sends a broadcast message to all base stations under its control. The message contains the number of the mobile station that is being called. The base stations then broadcast the message on all forward control channels (FCC). The correct mobile station acknowledges the page, by identifying itself over the reverse control channel (RCC). The MSC receives the acknowledgment via the base station, and instructs the base station and mobile station to switch to an unused voice channel. A data message is then transmitted over the forward voice channel, which instructs the mobile phone to ring [7].

The steps explained above happen fast enough that the user does not experience any noticeable delay between placing a request for a call and the call being connected.

The Protocols Used

Communication networks make use of protocols to facilitate communication between different entities within a network. A communication protocol is a set of messages and rules that correspond to messages communicated between two or more entities on a network. A network entity usually makes use of a whole set of such protocols, which are organized into a layered stack. Each of the GSM entities mentioned in the previous section has such a protocol stack. Figure 2 shows these stacks for GSM entities.

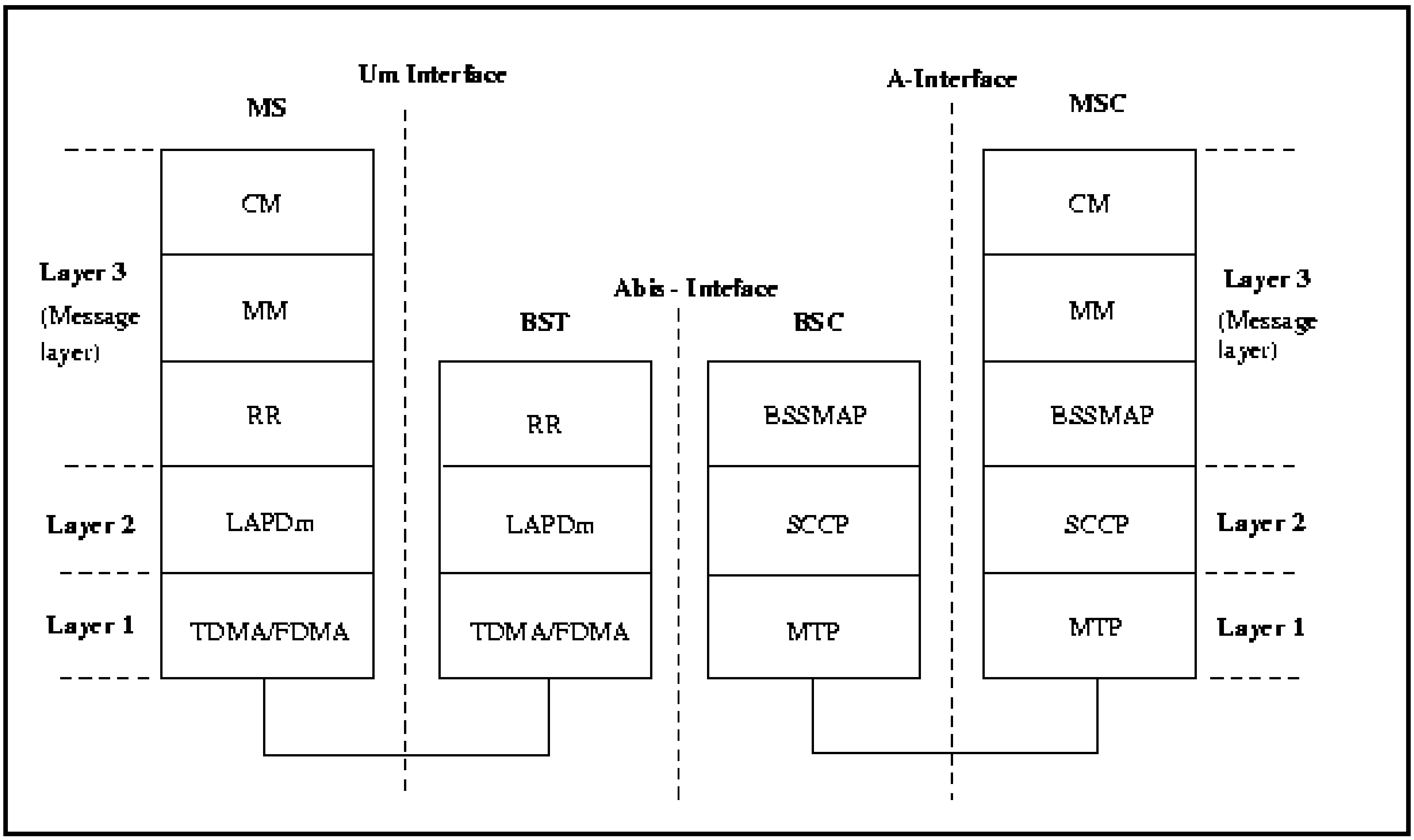


Figure 2:GSM protocol stacks

The stacks in Figure 2 are implemented in hardware or software, depending on the nature of the entity it resides on. In order for different protocol developers to write interoperable code, the European Telecommunications Standards Institute (ETSI) has produced a set of specifications to follow when implementing GSM protocols [14]. The specifications describe standard interfaces between protocols, which allow different implementations of protocols to interoperate because of the standard interfaces between the protocols. These interfaces are shown as dotted vertical lines between the GSM entity protocol stacks in Figure 2.

Detailed descriptions of the GSM protocol are beyond the scope of this article. The interested reader is referred to [14] for more details. The following is a general overview of the more important protocols within the protocol stacks. The networking concepts mentioned, such as the OSI reference model, can be looked up in any good networks textbook such as [11].

The GSM protocol stacks correspond to the OSI reference model; layers 1 and 2 of the GSM model correspond to the physical and link layers as defined by the OSI model. The physical layer specifies how data is transmitted from one entity to another across the physical transport medium. The physical transport medium between the MS and BST is the ether (air). Data is transmitted across the ether by modulating electromagnetic radio waves. As Figure 2 shows, a TDMA-based protocol is used to multiplex data onto the shared medium. An more detailed explanation will be discussed in the section below called *Radio Link Overview*.

The physical medium between the BSC and the MSC is a landline or microwave based E1 trunk, and the protocol used is the MTP level 1 protocol of the SS7 protocol suite [6].

The link layer provides a link between the networking layers above it, and the physical layer below it. It provides error detection and correction of packets received from the physical layer. A modified LAPD protocol, called LAPDm, is used over the *Um interface*. The MTP level 2 protocol of the SS7 protocol suite is used over the *A-interface*.

The similarity between the GSM protocol stack and the OSI model ends at the link layer. Layer 3 of the GSM protocol stack does not correspond to the network layer of the OSI model. GSMs layer 3 is composed of 3 parts, which is known as the message or signaling layer. It is used to set up and maintain voice circuits between users of a mobile cellular network. It does this by managing radio resources, information about user whereabouts, and voice circuit information. These operations are all specific to cellular radio networks because other networks do not have to keep track of user whereabouts or movement of users from one cell to another. The details of the layer 3 protocol span many ETSI specifications, of which the longest one is the MAP specification, which spans more than 700 pages [14]. The three sublayers of layer 3 are:

- Radio resource management layer - RR
- Mobility management layer - MM
- Communication management - CM

Discussed next are the operations of these three layers because they provide insight into the operation of a GSM network.

Radio Resource Management

The radio link between the MS and the BST over the *Um interface* makes mobile communication possible. By using the ether as transmission medium, users can gain access to communication networks without being physically connected. Communication over the ether does have its drawbacks. The radio spectrum available for cellular communication purposes is limited. Therefore, the available radio spectrum has to be used efficiently.

The cellular configuration of the network is designed with this restriction in mind. The radio resource management protocol's job is to manage radio resources as efficiently as possible by using the cellular configuration. It does this by taking care of the following responsibilities:

- The setup and maintenance of voice calls.
- The handover control of a call from one cell to another.

The setup of calls is accomplished through a polling scheme. The protocol uses a control channel that exists permanently between mobile stations and base stations. The control channel is used to send a request for a call setup from base stations to mobile stations. The mobile station continually polls the channel for connection requests. If the mobile station and the necessary radio resources (available communication channel) are available, the protocol sets up a dedicated voice circuit. By using this scheme, voice circuits only exist when necessary, and then get destroyed. The control channel uses a minimal amount of radio frequency, and therefore frequency is conserved by minimizing the existence of voice circuits to the times when they are needed.

Once a voice circuit is created, it needs to be managed because mobile stations move from one cell to another. While a call is in progress, the voice circuit sometimes needs to be transferred from one base station to another (when the cell it moves to is not served by the same base station as the one it came from, see Figure 1). The MSC and mobile station use the radio resource management layer to coordinate this procedure. The procedure is called handover or handoff and is quite a complicated procedure. It is described in detail in [10, 7, 1].

Mobility Management

It is necessary for the network to monitor the location of every registered mobile station in order for the mobile station to connect to the network upon request. The management of mobile station location information is handled by the mobility management scheme. The scheme operates by mobile stations registering themselves with the BSC that the mobile station is currently located. A centralized database stores a list of all the mobile stations in the network, and the BSCs they are currently registered with. A distributed database system is used to synchronize the database at the BSC and the centralized database at the server provider's premise.

Figure 3 illustrates how the scheme works. A mobile station (little car) arrives in a cell served by some BSC. It sends a message identifying itself to the BSC. The BSC sends this message to the MSC, which enters the identity of the mobile station in its visiting location register (VLR). The MSC then notifies the server on the service providers premise that it must update the home location register (HLR) with the new information about the mobile station's location.

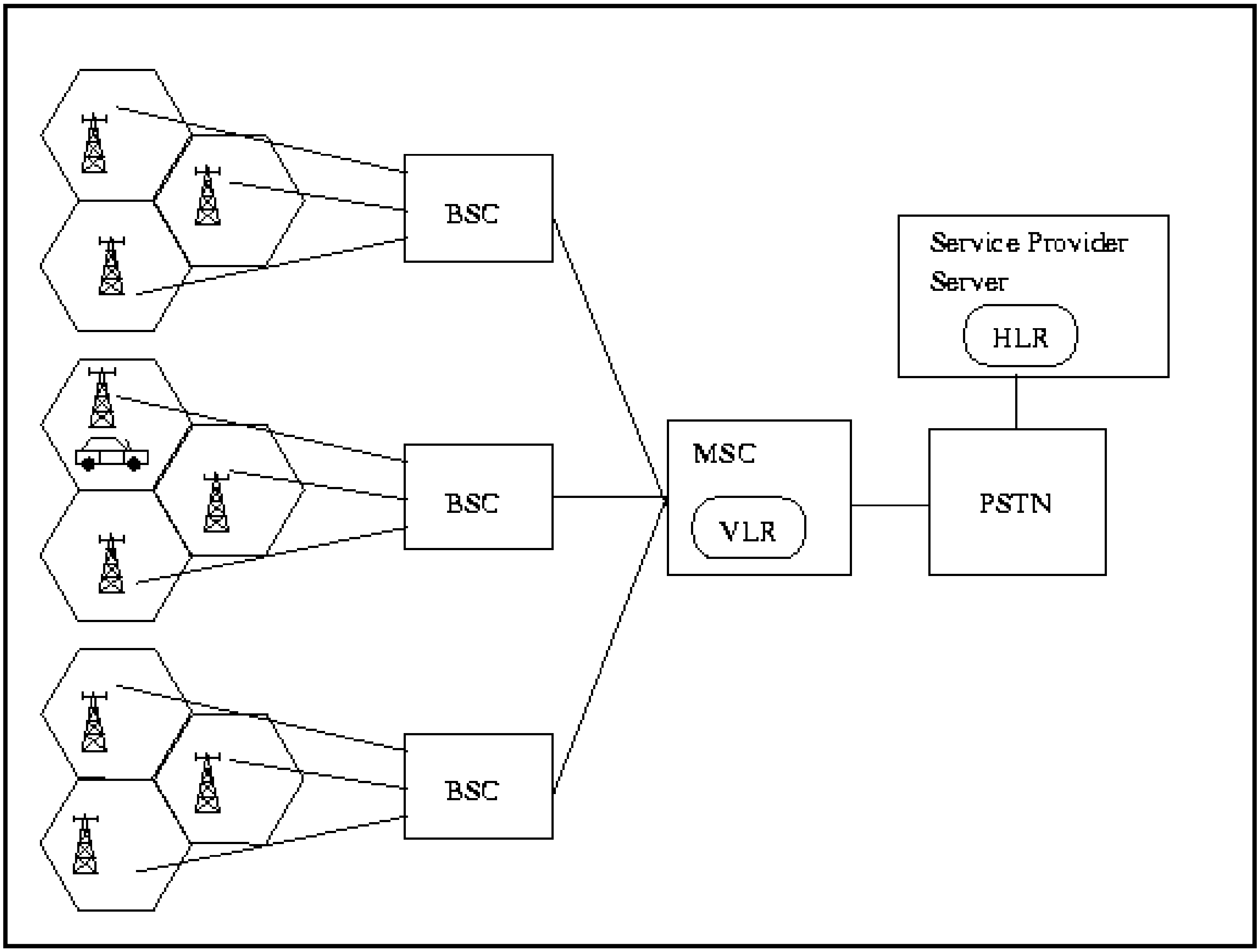


Figure 3:GSM cell topology

The mobility management scheme therefore consists of a distributed database (the VLR and HLR), and an associated protocol (the MM part of layer 3) to maintain location information of all the mobile stations on a network.

Using this scheme, a query to the centralized HLR is all that is necessary to find the current location of a mobile station. In order to keep the HLR current, a considerable amount of information is transmitted across the network. The HLR is updated every time a mobile station moves from one BSCs area into another. As the number of subscribers on the network increases, the information flow of updates to the HLR increases exponentially. Refer to [1] for information on mobility management techniques that minimize information flow by means of optimized algorithms.

Mobility management is also responsible for the authentication of mobile stations to the network. Mobile stations entering an MSCs area must be authenticated before they acquire the network's resources. This ensures that only valid customers make use of the network. Refer to [1] and [10] for more information on authentication procedures.

Communication Management

The communication management (CM) protocol of layer 3 is concerned with the setting up of calls. The call setup procedure was explained in the *How Does it Work?* section above. Apart from these procedures, the CM protocol also handles procedures to facilitate *roaming* on cellular networks. Roaming is a service that enables customers of a particular network operator to make calls from areas not served by that network operator. The network operator within the area of the call initiation contacts a Gateway MSC (GMSC), which links the user to its own network operator.

The GMSC identifies a caller's network operator by looking it up in a table. It makes use of a mobile station ISDN number (MSISDN), which uniquely identifies a mobile station [10]. The MSISDN is passed to the GMSC by the caller requesting a call set up. The MSISDN number is shown in Figure 4. It consists of a country code (CC), national destination code (NDC) and a subscriber number (SN). After having identified the caller's network operator, the network operator's HLR is queried to establish the location of the called mobile station. The call is then set up in the normal fashion.

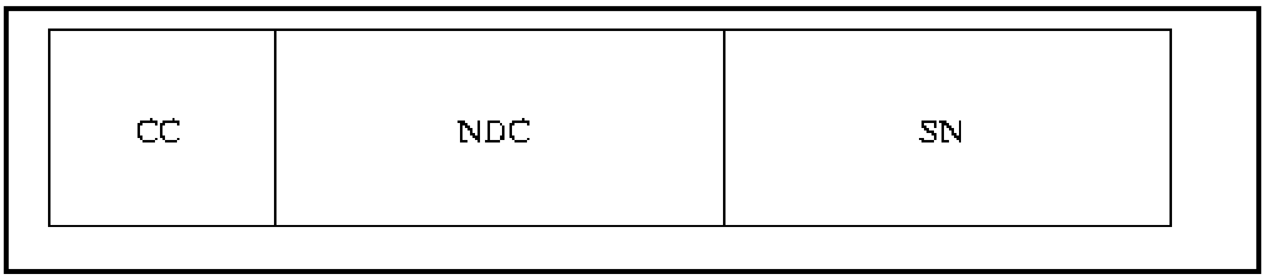


Figure 4: The structure of the GSM MSISDN

Radio Link Overview

As mentioned in *The Protocols Used* section, the physical layer between the mobile station and the BST use radio waves to transmit data, and is therefore called the radio link. In order to transmit speech across the radio link, the original analog representation of speech is changed into a digital representation, through the use of a speech coder. The speech encoding scheme that is used by GSM is called the *regular pulse excited, linear predictive coder* (RPE-LPC) encoding scheme [10].

This particular encoding scheme can encode speech into digital format efficiently enough to facilitate good speech quality on transmission channels with data rates of 13.4 kbps. GSM user channels have a capacity of 33.854 kbps for every user. After overhead is added to the RPE-LPC frames, user data is transmitted at a rate of 24.7 kbps, which is well within the limits of the channel capacity of 33.854 kbps [7]. GSM systems operate in a discontinuous transmission mode, which means that no data is transmitted during a user's silent period. Since each person on average speaks no more than 40% of the time, this scheme enables RPE-LPC to be used even more effectively [11]. The well known pulse code modulation (PCM) encoding scheme used in most public switched telephone networks (PSTN) is not used in GSM as it outputs data at a rate of 64 kbps, which is too expensive for GSM.

After speech is encoded, it is transmitted across the radio link by means of a digital modulation scheme.

Modulation is the process that encodes information into a form suitable for transmission over a specific medium, which in our case is the ether [7]. The modulation scheme used by GSM is called 0.3 GMSK (Gaussian Minimum Shift Keying). See [7] for an indepth explanation of GMSK.

The radio link has a limited amount of radio frequency to use for the transmission of data. The radio frequency available to network operators has been assigned to them by the ITU World Radio Conference in 1995 [1]. Cellular networks were allocated approximately 50MHz (2*25MHz bands) of radio spectrum by this Conference [1].

It therefore makes sense to use available frequency as efficiently as possible. GSM makes use of a TDMA/FDMA multiple access scheme to facilitate the efficient use of frequency. Frequency division multiple access (FDMA) is used to divide the allocated frequency up into smaller frequency bands, each used by different communicating partners. These bands are called *carrier frequencies* in GSM, and the two 25MHz bands (forward and reverse links) are each divided up into 124 such carrier frequencies. Carrier frequencies are allocated to base stations, making sure that interference does not occur by the same frequencies being allocated to base stations in close proximity to one another.

Time division multiple access (TDMA) is used to divide each of the carrier frequencies into *communication channels*. Each carrier frequency is divided into eight communication channels by means of TDMA. This means that there are 992 (124*8) traffic channels available on both the forward and reverse links. TDMA achieves the division of a carrier frequency into eight channels by dividing it into sequential time slots. Each user is allocated a unique time slot during the duration of a call. Data frames from different users are transmitted in their respective time slots and then reassembled at the receiver.

The Future

"The holy grail of the telephone world is a small cordless phone that you can use around the house and take with you anywhere in the world - it should respond to the same number, no matter where you are," was Tanenbaum's [11] definition of PCS (Personal Communication Services) in 1996. Since then the meaning of the term has evolved. It now takes into consideration the fact that data services have changed the landscape of mobile communications. Current GSM networks not only provide voice services, but data services at 9.6 kbps. Now, the meaning of PCS not only encompasses the delivery of voice services to people regardless of location, but also that of data services regardless of location, network, or terminal used [4].

The universal mobile telecommunications system (UMTS) proposes to achieve this ideal of PCS data, which includes services that are independent of location, network, or terminal. This system is hailed as being the next generation cellular system, and is referred to as 3G Cellular [8]. In order to attain this ideal, all interest holders of the cellular world will have to work together to standardize communications.

The ideal is a tall order. Other than integrating telecommunications networks, it envisions data transfer rates of up to 2Mbps [4]. Although the ideal will not be realized in the next few years, cellular networks are incrementally upgraded to provide better data transmission capabilities. The next section outlines the current state of data communications within GSM, and the plans to extend GSM to eventually become UMTS. The road ahead for other cellular radio network architectures will be very similar to that of GSM.

The Road to 3G Data

Current data services are constrained by the 9.6 kbps limit on the transmission speed of GSM radio links. This transmission rate is already being used to provide data services to network users.

PC cards are used as interfaces between PCs and mobile phones, allowing PCs to connect to data networks via mobile phones. The GSM network is digital, therefore data modulation and demodulation does not occur as it does with data transmission on the public switched telephone network (PSTN). Data is transmitted from the PC to the handset through the PC card. The handset transmits the data received directly onto the GSM network [4]. Data transmission and fax applications for mobile phones are already using such technology [4].

The GSM standard includes a service called SMS (Short Message Service). This service provides a two way paging capability based on store and forward principles. A mobile station can send a text message of up to 160 characters to another mobile station. If the other station is not powered on, the message is stored on a SMSC (Short Message Service Center) and then transmitted later [4]. This data service is used to provide notification services, such as email notification, emergency messages, news updates, stock market updates, advertising, and any other service that makes use of short text messages [3].

High-Speed Circuit-Switched Data Service - HSCSD

The current limitation of 9.6 kbps over the radio link is due to the fact that only one of the eight possible TDMA channels is used for data. This limitation has been alleviated slightly by using less error checking, which raises the transmission rate to 14.4 kbps in the parts of the network that can afford to use less error checking [4].

The obvious way to increase transmission rates is to use more than one channel for data transmission. Currently being tested is a service called high-speed circuit-switched data service (HSCSD) [8]. This service combines two to four of the channels for data transmission to attain rates of 28.8 and 56 kbps [8]. Such data rates open a whole new world to cellular radio networks. Users will be able to connect to the Internet and their own dial up network servers through the GSM network. The GSM network provides encryption as a standard service [2], therefore the implementation of Virtual Private Networks on GSM networks is a natural extension of data services already provided.

General Packet Radio Service - GPRS

The increased transmission speeds attained by HSCSD does not completely solve the data transmission problems of cellular networks. The GSM network is circuit switched (SS7), and therefore a complete virtual circuit is set up every time data or voice is transferred from one point to another across the network.

Most of today's network applications are bursty by nature, and rely on sending small amounts of information at irregular intervals, e.g. email. It is very inefficient to create a virtual network circuit every time a user transmits a small amount of data. To address the problem, a service called general packet radio service (GPRS) is in the process of being developed [9].

The idea is to allow users to connect to packet switched data networks (IP and X.25) via a separate connection than the voice network. The two services will run in parallel. A user will be able to log onto the GPRS network, and gain access to any IP or X.25 network [9]. When connected to the network, the user will only pay for the amount of data transferred, as opposed to the time spent connected to the network. The user will be able to accept incoming calls during a data transmission [9].

A GPRS network will be able to use all eight of the TDMA channels, sustaining data rates of up to 164kbps, if the external network the GPRS network interfaces with can sustain these rates. In order to implement GPRS, an extra node needs to be added to the GSM network architecture. This node, called the gateway GPRS support node (GGSN), forms the interface between the Mobile Station and the packet switching network (IP or X.25) [8].

Enhanced Data Rates for GSM Evolution - EDGE

EDGE is the natural extension to GPRS. It uses the same network layer as GPRS, but is based on a new physical layer [8]. The physical layer is designed to transfer data at extremely high rates. This service is considered a third generation cellular service and is expected to deliver data transmission rates of up to 500 kbps, under very good conditions.

Wideband CDMA - WCDMA

Wideband CDMA will be the final third generation cellular architecture. It will be based on CDMA technology, but will use the same data networking system as EDGE/GPRS [8].

Value Added Services

Cellular network operators have to be at the forefront of technology to survive the extremely competitive cellular network environment. Network infrastructures must continually be upgraded, and new applications and protocols need to be developed that provide novel services to customers. Industry analyst, Andrew Seybold, stated that inefficient use of these advances in data transmission technologies, "could be a significant windfall for network providers who are interested in obtaining and keeping new customers" (Seybold's Outlook, August 1998) [5].

To this effect, network operators are developing value added services (VAS). These data services are provided to users over and above the standard network services of voice transmission. Three technologies are being developed in order to make the development of these services possible for network operators. These technologies are: wireless application protocol (WAP), SIM application toolkit (STK), and Bluetooth.

WAP

WAP enables wireless devices to transfer information in a reliable and effective manner. The constraints of wireless medium forced developers to create a protocol that allows for the low bandwidth and unreliability of the wireless medium to be used effectively. WAP has an optimized protocol stack, and uses a mark-up language at the application layer - WML and WMLScript [12]. It uses UDP instead of TCP, due to the unreliability of the radio link. It has transaction and security layers, which were included to enable the development of applications allowing secure business transactions [12].

The WAP model interposes a WAP gateway between traditional web servers and WAP clients. The gateway translates HTML into WML, and compresses it into a binary form that is used to save radio-link bandwidth. The client has a WAP browser, which interprets the compressed binary files.

STK

STK, defined in GSM 11.14, defines an interface between the subscriber identity module (SIM card) and the cellular handset. Consequently, applications loaded onto the SIM card can be run via the handset interface. Network operators need a computational platform to run data applications on telephone handsets. Although handsets do not provide a uniform platform; network operators have complete control over the SIM cards they supply to their customers. SIM cards are therefore the ideal vehicle to implement and distribute applications. The SIM card also provides built in security, which is useful for business applications.

Applications will be available for download over the air from network operators, and users will be able to add and remove applications from the SIM card as needed. Sun has developed a Java card, which runs Java programs and uses the STK interface.

Bluetooth

Bluetooth is a technology allowing mobile communication devices like handsets and mobile computers to communicate without the use of cumbersome cables and software drivers [5]. It is a joint effort by Ericsson, IBM, Intel, Nokia and Toshiba to make mobile data applications less cumbersome to use. A laptop PC will be able to communicate with a mobile phone, even if the phone is in another room. Used in combination with GPRS, a laptop will be permanently connected to a packet switching network through the mobile phone. A user will only pay for data transmitted over the network. A mobile phone will be able to notify a laptop when an incoming email has been received, allowing the user to decide whether to pay for downloading the email to the laptop.

Conclusion

Cellular radio network infrastructures are growing at a tremendous rate. People are purchasing mobile phone contracts because they provide a useful and relatively cheap service. The services provided by network operators are being extended to include data services. Geographical coverage of networks is enlarged by means of global roaming.

Cellular networks are becoming high speed data networks. The cellular user base is mobile and extremely large. Consequently, development of mobile data applications depends upon the development of new communication protocols.

Industry is working on speeding up the development of mobile communication technologies. The ideal communication system where both voice and data services can be delivered regardless of location, network, or terminal may be in the near future.

References

1

Akyildiz, McNair, et al. Mobility management in next-generation wireless systems. *Proceedings of the IEEE*, August 1999.

2

Barth, D. Privacy issues in mobile data communication. Internet - http://www.gsmdata.com/today_papers.htm , May 1998. Last Accessed: 28/02/2000.

3

GSM data knowledge site. Internet - http://www.mobiledata.com. Last accessed: 28/02/2000.

4

K. Holley and T. Costello. The evolution of GSM towards UMTS. Internet - http://www.gsmdata.com/today_papers.htm, February 1998. Last Accessed: 28/02/2000.

5

S. Nachtsheim. Bluetooth technology - the convergence of computing and communications. Internet - http://www.gsmdata.com/today_papers.htm, February 1999. Last Accessed: 28/02/2000.

6

Rahnema, M. "Overview of the GSM system and protocol architecture." *IEEE Communications*, April 1993.

7

Rappaport, T. S. *Wireless Communications*. Prentice Hall, 1996.

8

Rysavy, P. The evolution of cellular data: On the road to 3G. Internet - http://www.gsmdata.com/today_papers.htm, 1999. Last Accessed: 28/02/2000.

9

Rysavy, P. General packet radio service - GPRS. Internet - http://www.gsmdata.com/today_papers.htm, 1999. Last Accessed: 28/02/2000.

10

Scourias, J. Overview of the global system for mobile communications. Internet - http://www.gsmdata.com/overview.htm, October 1997. Last accessed: 28/02/2000.

11

Tanenbaum, A. S. *Computer Networks*. Prentice Hall, 1996.

12

Wap forum. Internet - http://www.wapforum.com. Last Accessed: 28/02/2000.

13

Zeng, Annamalai, et al. Recent advances in cellular wireless communications. *IEEE Communications*, September 1999.

14

ETSI - European Telecommunications Standards Institute. Internet - http://www.wapforum.com. Last Accessed: 18/05/2000.

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