7

Clock Systems in Networks

7.1 Wired Systems

7.1.1 Clocks in Digital Systems

Clock signals are containers that carry the physical quantity of frequency. Frequency is transferred across digital systems by the clock in a way that is different from the one in analog systems. Clocks are a new part of digital systems.

Digital systems are either synchronous or asynchronous. In the former case, all system elements utilize the same reference clock, while in asynchronous systems they do not. Current telecommunication networks, especially long-haul transmission networks, are basically synchronous. In each such network, the clock is synchronized and shared. It conveys the common frequency used to synchronize the network elements. In this configuration, the clock distribution area constitutes the whole network. Each asynchronous network, on the other hand, may have many clock distribution areas, each of which is usually formed between neighboring functional blocks. The physical separation between functional blocks varies from neighboring integrated circuits to several or several tens of kilometers.

Synchronous and asynchronous communication both require that the clock be transferred to the intended destination. The transfer process is a basic item for any system. In a synchronous system, the clock is distributed from the master node, which acts as a reference. This reference clock is regenerated at all other nodes and further transmitted to all systems in each node.

Since all circuits in the network use the same clock (i.e., same frequency accuracy) this method makes it easy to multiplex/demultiplex and add/drop information using registers. If the clock frequency deviates from the reference clock, information loss can occur, and in the worst case, communication might fail. In asynchronous systems, since the frequency is not synchronized, the individual elements are insensitive to clock frequency deviation. However, these systems require additional mechanisms that can prevent information loss, which would otherwise result from the frequency difference.

A network that transfers information packets, such as the Internet, can be realized either as a synchronous or as an asynchronous system. Asynchronous transfer mode (ATM), which uses labeled packets called cells, has been deployed into telecommunication networks. An ATM transmission system is normally realized using the frame format of synchronous digital hierarchy (SDH), which is basically a synchronous method. Note that an asynchronous configuration was considered in the original development phase. Ethernet, originally developed as a local area network (LAN) standard, is a completely asynchronous system. Even the more recent Gigabit Ethernet is asynchronous. Designing a synchronous system demands some assumptions as to network scale and the type and number network elements used. Designing an asynchronous system appears to be easier in that each element can be designed more independently. Most internal circuits, however, use synchronous mechanisms. Since synchronous systems support higher clock frequencies, which means faster data rates, they have become more popular over the last few years.

7.1.2 Clocks in Transmission Systems

In basic digital communications, the clock of the sending site should be used on the receiving site as well. The sending site generally transmits the common clock together with the information [1]. This enables the receiving site to regenerate the information. The clock is distributed independently of associated information on the circuit level, but these two share the same medium (cable, radio carrier) in the transmission system. This is natural because the transmission medium cost dominates in long-haul systems. This sharing, however, leads to a problem. If the receiving site loses the clock, information too will be lost. Each transmission code has its own merits and weaknesses. The non-return to zero (NRZ) code, adopted in the SDH system, is the most popular transmission scheme in current networks [2]. If the data stream consists of a succession of either all 0s or all 1s, the receiving site loses the clock. To prevent this, the final circuit at the sending site scrambles the signal. This evens out the occurrence frequencies of 0s and 1s [3]. The receiving site descrambles the received data stream to get the original data.

Figure 7.1 shows a transmission clock system. Information on the sending site is converted into the data stream according to the transmission clock generator. It also hosts the clock changing circuit from which the converted data is released to the transmission path. The converted data holds both information and clock components. The receiving site needs a clock recovery circuit and an information regeneration and discrimination decision circuit. The transmission clock recovery circuit receives the data stream from the transmission path, and extracts only the clock component. The information regeneration and discrimination decision circuit uses the extracted clock to regenerate the original information. Noise added in the transmission path is removed by the transmission clock recovery circuit, and the regenerated information is output by the information regeneration and discrimination decision circuit

7.1.2.1 Transmission Clock Generation Circuit

The transmission clock generation circuit must generate the clock with the specified frequency accuracy. If the frequency of the data stream does not lie within the specified range, the clock cannot be properly extracted because it is outside the synchronization range of the clock recovery circuit at the receiving site. Receiving errors or information loss consequently occur. Long-haul SDH transmission systems demand frequency accuracies of 20 ppm (20×10^{-6}) or better. Small quartz oscillators are suitable for achieving such frequency accuracy. Unfortunately, such oscillators do not cover all frequency ranges. Figure 7.2 shows how we can generate a clock for the gigahertz frequency region using a quartz oscillator that directly generates 155 MHz. The example in Figure 7.2 is actually used in SDH systems [2]. The output of the 155.52-MHz quartz oscillator is converted into 2.48832 GHz in the PLL.

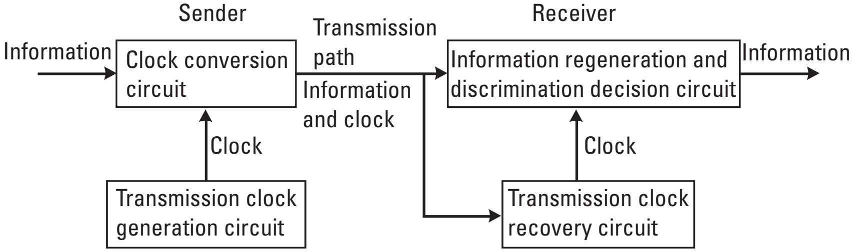

Figure 7.1 Typical clock arrangements in a transmission system.

Figure 7.2 Clock generation in the gigahertz frequency region.

The converted clock corresponds to the clock frequency of an STM-16 transmission system. Figure 7.3 shows a schematic of a commercial clock generation IC [4]. The clock for STM-16 is generated from the frequency of 155.52 MHz by the PLL. The multiplexer is installed in this IC. Sixteen data signals, each 155.52 Mbps (STM-1), are multiplexed, and the data stream of 2.48832 Gbps is output through the data discrimination decision circuit. A 10-Gbps clock generation circuit (STM-64) will enter the market soon [5].

7.1.2.2 Transmission Clock Recovery Circuit

The transmission clock recovery circuit must reliably extract just the clock component from the transmitted signal. The first task is to suppress the effect of noise coming from the transmission path. In addition, the clock must be recoverable from any transmitted signal. The direct approach is to use a filter as a clock recovery circuit. The most generic clock regeneration approach consists of an LCR circuit and a piezoelectric quartz resonator. Recent demands for higher resonant frequencies, better frequency stabilization, and lower costs have forced the clock recovery circuits to employ PLLs as shown in Figure 7.4. A transmission clock recovery circuit with a PLL (which offers phase synchronization) generates the same frequency as the initial frequency component in the transmitted signal. At the same time, transmission path noise is suppressed by the lowpass characteristic of the PLL.

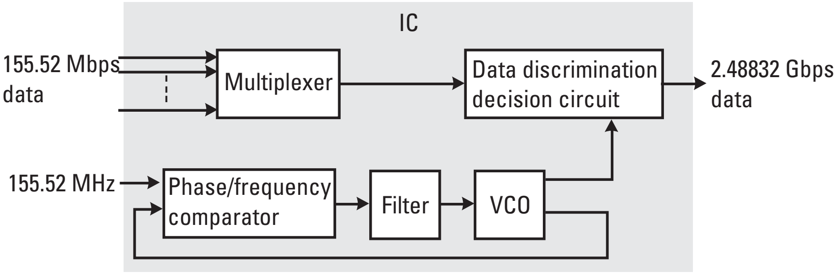

Figure 7.3 An example of a clock generation IC suitable for transmission systems.

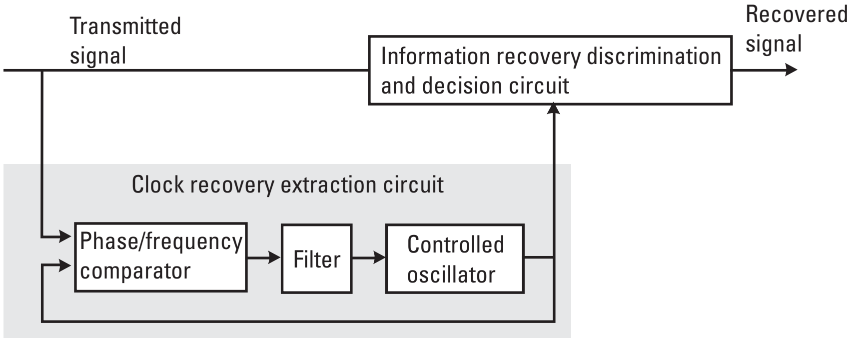

Figure 7.4 Signal receiver with a recovery circuit using a PLL.

A resonator-based clock extraction circuit needs a high Q value to remove noise. The output phase of a resonator, however, will change when the center frequency shifts from the clock frequency of the sending node. Thus, the phase margin in the clock recovery circuit becomes small, which raises the error probability. Since this tendency is proportional to the Q value, there is an upper limit for it in resonator-based clock recovery circuits. Also, the noise reduction possibilities are limited. On the other hand, in PLL clock recovery circuits, noise can be sufficiently suppressed by selecting the cutoff frequency of the lowpass characteristic. The steady-state phase error in PLLs can limit the phase margin in the information regeneration discrimination decision circuit. Second-order PLLs with passive filters are often used to solve this. Unfortunately, such PLLs exhibit a lowpass characteristic with positive gain. This means that a series connection leads to noise accumulation. It is necessary to decide PLL parameters such as the filter configuration considering the noise characteristics of the whole network.

7.1.3 Clock System for Network Synchronization

All elements in a synchronized network must use the same clock. At any healthy node in the network, the total amount of information coming in always equals the total amount going out. This network type has a significant advantage: multiplexing/demultiplexing and adding/dropping of information can be simply and easily achieved by digital processing. If the clock frequency shifts from the nominal value, the transmission quality deteriorates. Clock generators must meet strict specifications such as frequency accuracy and stability [6–8].

The reference clock is distributed from the master node to all other nodes using star and/or hierarchical structures. The components forming the clock distribution network that links the master node to the slave nodes are shown in Figure 7.5. The reference clock at the master node becomes the unique master clock for the network. A cesium atom standard is usually used for this purpose due to the demanding requirements [6]. Alternatively, a GPS disciplined rubidium unit may be sufficient. The slave clock in each node must satisfy three points:

1. Receive and regenerate the reference clock transmitted from the master node, which requires that the noise caused by the transmission process be reduced.
2. Supply derived clocks that have the appropriate frequencies to the node's systems.
3. Continue clock supply if the reference clock fails for whatever reason.

Slave clocks that can achieve these points generally have the configuration shown in Figure 7.6. The PLL has the frequency keeping (holdover) function to maintain the required clock frequency accuracy when the reference clock fails [7]. A redundant system configuration is generally adopted to

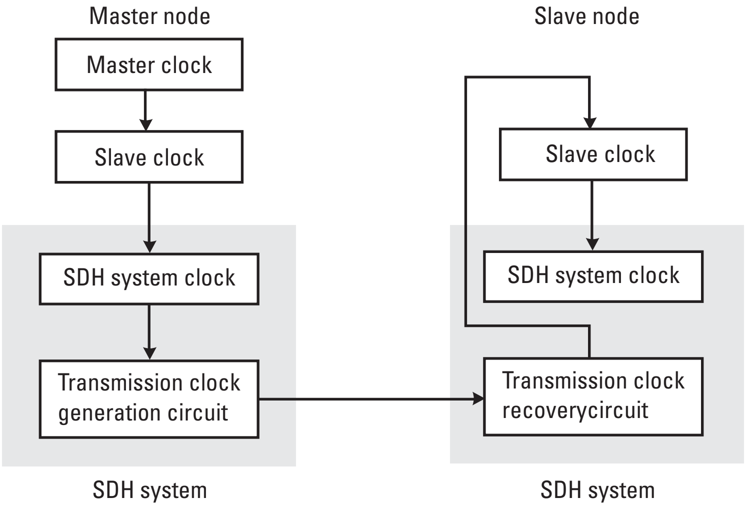

Figure 7.5 Clock arrangement for SDH network synchronization.

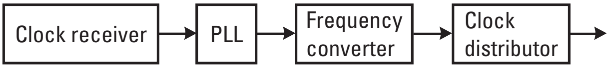

Figure 7.6 Slave clock configuration.

ensure reliability. The PLL design methodology for slave clocks is described in Chapter 8.

The SDH system lies within the shaded area in Figure 7.5. It consists of SDH system clocks, transmission clock generation circuits, and transmission clock recovery circuits. The SDH system clock receives its reference from the slave clock and generates a clock with the specific frequency used in the SDH system. In addition, the SDH system has a function to hold the required frequency accuracy to avoid the impact of slave clock failure. Transmission clock generation/regeneration is a basic feature of transmission systems such as the SDH system as described in Section 7.1.2. The signal generated in the transmission clock generation circuit is transmitted to the slave node (the right side in Figure 7.5) and recovered in the clock recovery circuit of the respective SDH receiver circuit. The transmission clock from the clock recovery circuit is directly passed to the slave clock and it becomes one input of the clock receiver (see Figure 7.6). By repeating this process, the reference clock is transmitted from node to node, and the reference clock is distributed to each element in each node. All clocks throughout the network can be synchronized by this process.

7.1.4 Clock System Across Multiple Links

In a synchronous system, the clock is transferred by passing it through the components shown in Figure 7.5. This configuration connects many PLLs in series. The phase variation that can occur as the clock transits a path can be propagated and often amplified. Even a transient response, which is not a severe problem in a single PLL, might become a significant cause of phase variation. If the damping coefficient of a second-order PLL (see Section 5.4.1) is small, and there are phase and frequency variations in its characteristics, a lot of time will be needed to stabilize the phase. This phenomenon is equivalent to the PLL transfer function having positive gain over the frequency range, as shown in Figure 5.16. This gain occurs in each link of the PLL chain, and the phase overshoot is magnified at the last node of the chain. There are two elementary solutions to this problem: restrict the number of linked PLLs or completely separate the transfer functions of the individual PLLs. These two tricks tend to be impractical. The more practical remedies are as follows:

1. Reduce the transfer function gain.
2. Make the transfer functions of the PLLs (the slave clock, the SDH system clock, and the transmission clock generation circuit) different.
3. Select a larger damping factor in the slave clock and the SDH system clock since they have a larger margin in terms of the maximum synchronization time.

7.2 Wireless Systems

7.2.1 The Effects of Network Topologies on Clock and Frequency Synchronization

Modern technology has enabled very flexible cable-based digital communication networks in which a strictly predefined communication hierarchy is no longer necessary. The ultimate requirement of unlimited mobility [9], however, has pushed the respective solutions of some radio communication networks even further, and it is thus appropriate to consider some the typical topologies separately. The associated frequency and synchronization issues, related difficulties, and selected solutions will be pointed out with an emphasis on the different systems used to transport a digital baseband signal.

7.2.1.1 Point-to-Point Communications

Two distinct classes of point-to-point radio frequency communication arrangements can be found. The first, and perhaps the more straightforward one, is a microwave link, which forms the communication path between two physically separated but stationary nodes of a larger network. This solution is selected either due to geographical constraints, which would make a fiber optic connection impractical or due to synergies with other transmission systems (shared use of antenna towers, etc.). We usually find symmetric capacity in both directions, although this is not necessary. In these cases the problems of synchronization are normally not very severe, particularly if an all-digital link chain is in use. The radio frequency dimensioning provides an adequate carrier-to-noise ratio, there is seldom any measurable multipath due to the very high gain antennas, and timing jitter should only become a real problem in extreme environmental conditions and at very high data rates. Such circumstances include tropical rainstorms, heavy-wet snow, and wind speeds above 30 m/s. Water or snow particles will simply cause a huge additional attenuation whereby the connection will be temporarily lost. Winds, however, might cause large enough distortions of the tower installation itself to disturb the path delay profile. In fact, the receiving site would see a moving transmitter, and depending on the associated time constants, some of the synchronization (either carrier frequency or timing) might be temporarily lost.

Some mobile point-to-point communication systems exist as well. They are very often established for a dedicated mission of limited duration, and some can make use of radio interfaces, which are intended for a broader scope too. Sometimes both ends of the link are moving, but more often only one. A highly asymmetric capacity profile is commonly seen. Less conventional examples include an image transmission system for helicopter-based ice-monitoring to assist an ice-breaker or a military unmanned airborne vehicle (UAV) light airplane used for reconnaissance tasks. Most commercially available systems utilize frequencies at or above the ultra high frequency (UHF, generally from 300 MHz) band due to size constraints. The radio frequency scenario is challenging both due to the continuously changing multipath and due to the Doppler processes involved. A typical detected synchronization signal is illustrated in Figure 7.7. The electronics on board the moving platform will face an adverse environment, which will be discussed in Section 15.2.2. Despite data rates often being very high and the reliability requirements exhaustive, a link between two users is still relatively

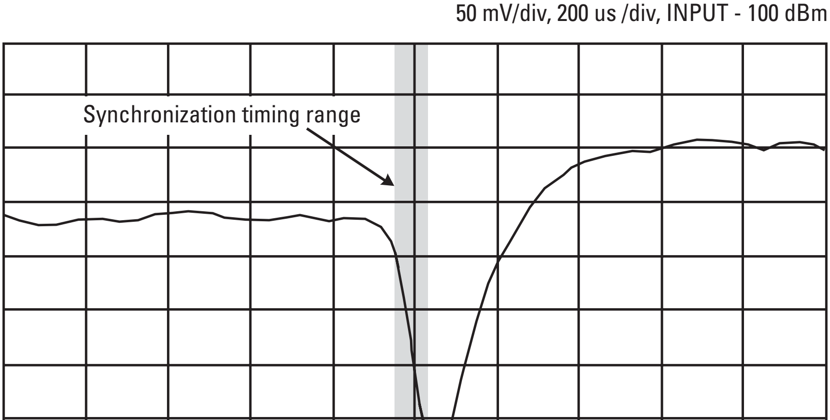

Figure 7.7 An example of the received synchronization signal in a mobile radio network.

easy to handle. Both the up and downlinks can use frequency steering and adaptive oscillator control without any concern for additional receivers or transmitters in the same system—because there are none! The whole time domain is available just for this traffic. If necessary, the two sites can be presynchronized prior to the mission, and very often there is some reserve bandwidth available whereby the system is not pushed against its theoretical capacity limits—as opposed to many dense multipoint solutions.

In addition to the two above-mentioned cases, many multipoint networks (like military high-frequency communication setups between 10 kHz and 30 MHz) can be operated as separate simple point-to-point systems, but even so, their technical arrangements tend to follow the original concepts.

7.2.1.2 Point-to-Multipoint Networks

Strictly speaking, this kind of a tree-like topology is not a true communication arrangement, except in a very few special cases. The topic must be included, though, because its most well-known application—broadcasting in all its forms—is currently being merged with the traditional communication functions. Technologically this network type is relatively easy to control if no or very limited uplink traffic is needed [10]. The arrangement is a typical master-slave system in which the frequency and timing control flows directly from the node towards the (normally) receive-only terminals, which is also the direction of data flow.

Some of the technical issues in this network category are quite interesting. The required data rates for live video broadcasting are among the highest, and the system may include both stationary and highly mobile users. Although human vision can be fooled to a certain extent—as has been done for decades in the old analog television systems—many transmission-related defects will turn up immediately. The transmitting node has typically no information about the behavior or state of the receivers (e.g., clock frequencies), and even if this were technically arranged, there would be hardly any means available to handle the amount of incoming data. So the communication must follow a blind transmission scheme and practically no means are at hand to recover lost data at a receiving site. A further technical complication is caused by the requirement for low-cost terminals, which should provide almost superior broadcasting quality even in adverse radio frequency conditions. Because normal radio and television programs include human voices, any temporary interruptions are very annoying and are thus considered unacceptable.

Simple carrier frequency tracking is easy to implement in the receiver units. An example of the performance of such an arrangement is shown in Figure 7.8. One of the greatest threats is still—after the introduction of

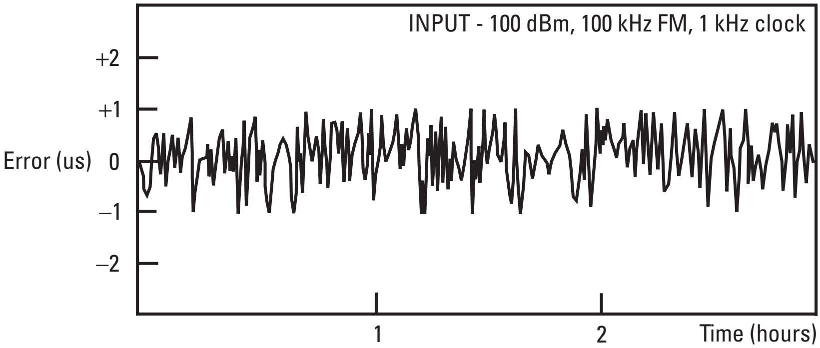

Figure 7.8 The measured performance of a frequency modulated carrier-tracking receiver.

orthogonal frequency division multiplexing (OFDM)—multipath propagation, which may cause the pattern synchronization to collapse [11]. This is the case particularly if a simultaneous combination of a high data rate with a high physical velocity is needed. A resynchronization action will often take too much time to be hidden from the end user of the communication terminal.

Other users of the point-to-multipoint concept are, for example, networks, which provide alarm messages to rescue forces. Here, however, the transmission data rates are normally very low and adequate service can be provided without dedicated radio frequency tricks.

7.2.1.3 Cellular Networks

Cellular communication networks were originally designed to transmit and receive human conversations. The first designs utilized an all-analog concept, and the main challenges were in providing a comprehensive geographical coverage at a minimum acceptable signal quality level. The requirement for frequency characteristics was just the maximum allowed frequency deviation including the clock frequency aging. The present digital networks follow the centralized control concept and must follow a fully synchronized principle in addition to real-time carrier frequency control.

Although the cellular network topology is based on a connection between the terminal and a base station or cell, the synchronization arrangement must take into account the other mobile units as well as the adjacent cells. In practice, all cells share a common data clock and preferably a common carrier frequency reference too. This can be easily derived from the first clock whereby phase continuity is assured also during modulation.

In terms of synchronization management, a cellular network is somewhere between a simple point-to-point system and a totally “free” ad hoc network (which is described next in Section 7.2.1.4). The individual cells, the base stations, and base station controllers form a fixed configuration having predefined delays and clock characteristics as has been outlined in Section 7.1. The mobile terminals (or, simply put, cellular phones), on the contrary, take arbitrary positions within the coverage area. They also have a relatively wide velocity range. Thus, there is a need to adjust for the varying time differences and to take into account possible frequency shifts. At present, most cellular networks use a form of feedback control, which is feasible due to the symmetric nature of the communication path. However, the time constants of the loop, which consists of the mobile terminal, the base station, and the communication paths, become longer. Unless better local clocks are used, the inherent synchronization quality will be deteriorated.

The challenges for synchronization are partly related to multipath propagation, which may be severe and highly fluctuating in a dense urban environment, and partly related to the technical realization of the oscillators in the mobile unit. Also, the evolution of data transmission needs from the simple human discussion towards Internet and real-time video has necessitated much higher clock speeds. Naturally, this leads to more and more stringent stability requirements. Similarly to the broadcasting environment, a cellular system is badly hampered by any retransmissions or resynchronization actions, as opposed to other wired digital communication.

7.2.1.4 Ad Hoc Networks, Multipoint-to-Multipoint Networks

Both modern commercial and military communication systems nowadays make use of an ad hoc concept in which no predefined radio network topology exists. The individual units have to follow a common standard but in addition to their completely arbitrary geographical location, their logical placement is freely arranged. Some of the networks may have limited forms of centralized control but this is not necessarily implemented. Typical examples are some short-range office systems operating in the higher microwave bands, tactical military UHF networks, and other systems intended for government authorities.

Clock and synchronization arrangements are extremely complicated in these radio networks if high data rates and availability factors are the goal. This is due to the unknown and constantly changing path delays and the variety of individual units. Each mobile terminal can at the same time be a node for several others, and frequent rerouting may occur. It is also possible that a device, which has initially been stationary and has served as a transfer node for a multitude of other terminals, suddenly starts to move. In such a case we have to cope with the relative frequency changes as well.

7.2.1.5 Mixed Communication, Navigation, and Broadcasting

A somewhat different synchronization task is met with the new systems where several radio-related functions have been combined inside a single mobile framework. For example, devices capable of simultaneously performing broadcast reception, personal navigation, and data communication have been introduced. Instead of thinking of such concepts as a simple physical merging of individual technologies, the efficient use of spectral resources and hardware and the wish for add-on services suggests that the whole operational idea be harmonized. This is a challenge to synchronization and frequency control but does provide new opportunities too.

Within any reasonable time span, we must assume that the original source networks used, for example, for broadcast data generation, will use their independent clock systems. A similar situation will apparently prevail inside the navigation community. Thus, the new network's designs and its individual mobile terminals must be able to resynchronize themselves "on-the-fly" as defined either by user preferences or technical constraints. On the other hand, we can assume that the increase in the available background synchronization references as seen by the terminal devices can be utilized to enhance the local clock performance. For example, low-cost mobile communication devices can reap the benefit of navigation-based clock stability to provide an error-free data link performance for their users.

7.2.2 Synchronization and Frequency Control Arrangements for Radio Networks

Many mobile communication systems follow a simplified step-wise scheme of synchronization. The radio frequency parts are first aligned either by using simple crystal oscillators, phase locked loops, or DDS circuits. After that, the baseband synchronization can start in the desired order. At the radio frequency interface, the frequency control activity is needed not only because of natural requirements of functionality but also because of the ultimate need of improved spectral efficiency. The smaller the uncertainties in the carrier frequency, the smaller the guard intervals need to be. The technological approach is somewhat different depending on the communication task, although the low-cost digital processing blocks have already started to take over almost everywhere. For historical reasons it is interesting to note that the first practical radio transmitter networks based on frequency synchronization were designed according to a German patent granted in 1933 [12].

7.2.2.1 Fixed Frequency, Single Carrier Systems

If the communication system has only one carrier frequency, which will stay constant both in terms of elapsed time and coverage volume, the frequency-generating technology has traditionally been the simplest one. If the operating band is low enough, direct crystal oscillators are preferred. In the past, when equipment density was very low, simple LC resonant circuits could be utilized whereby any arbitrary frequency value could be tuned but, of course, at the expense of stability. Higher frequency microwave signals are produced by PLL circuits and multipliers, which impair the stability in proportion to the order of multiplication. Harmonic mixers must be used to cover the highest microwave and millimeter wave bands to support the PLL units. As these systems have no need for frequency changes, all individual elements can be tuned to give the best possible performance.

7.2.2.2 Multiple Carrier Systems

Most radio communication networks have several carriers simultaneously in use, and at least the terminal devices must be able to make use of all of them. It means that they have to be able to change their frequency rapidly and accurately. Thus, simple crystals are not suitable but we need PLL-based synthesizers or, more recently, DSP generators. The frequency range is often not the most severe constraint because amplitude-based network planning normally favors carrier spans of only some tens of megahertz (at typical UHF frequencies). It is more challenging to provide the necessary frequency switching speed and the respective settling time to achieve the necessary frequency accuracy. This is particularly true for cellular networks during a hand-over action, which might be requested by a mobile device traveling at 100 m/s. In addition to this, the spectral purity is a major issue because of the heavy crowding of the available channels. Spurious emissions at one transmitting frequency may be seen as interference in the nearby receivers, which operate at a close-by frequency.

7.2.2.3 Frequency Hopping Networks

Slow or fast frequency hopping has been initially introduced to the military communication networks to provide some low-probability-of-intercept/low-probability-of-detection (LPI/LPD) characteristics. The idea is to change the transmitting frequency so rapidly that the opponent cannot find the transmitter by surveillance receivers nor can he try to jam its message.

The commercial communication networks started to use frequency hopping to reduce the effects of multipath, as will be suggested later by (15.2). The technical challenges are first to design analog circuitry (amplifiers, filters, antennas, etc.) that has a wide enough bandwidth and then to construct oscillators that are able to perform the very fast frequency switching action synchronously with the receiving installation. Initially, the devices have used special PLL circuits in which some compromises have been allowed for faster settling, but modern designs rely on the DSP concept as long as the frequency range permits. Here the difficulties in maintaining required spectral purity near the momentary carrier are even worse than in the more decent synthesizers because of the restrictions in filtering.

7.2.2.4 Spread Spectrum Communications

Despite frequency hopping networks often being seen as spread spectrum networks, real spread spectrum communications systems are implemented by extending the information (data) content of a signal over a much wider radio frequency range than required by modulation theory. So it need not be frequency hopping; nor are all hopping systems real spread spectrum.

The practical spreading action requires that the data synchronization be tightly bound to the RF generation process. This is best accomplished by using modern DSP circuits. If the desired frequency range is much higher than the capabilities of current digital blocks, it is always possible to use an additional upconverter after the DSP unit. Care should be taken to use adequate filtering in order to remove any local oscillator leakage from the output.

If needed, the spread spectrum scheme can be added to a frequency hopping system. This improves the protection of the content and will give additional multipath rejection in those systems where the baseband rate is low to medium. Normally the individual radio terminals have very high quality oscillators [either an ovenized quartz oscillator (OCXO) or rubidium] to enable autonomous operation. This means that, for example, an airborne communication link is completely locked before the mission and will stay so as long as the respective oscillators are able to maintain the required timing error. Synchronization over the air interface is strictly forbidden. It would unavoidably reveal the vital system parameters to the external observer.

7.2.2.5 Impulse Radio, Ultra Wide Band (UWB) Transmission

The impulse radio concept, now in use by some military units for short-range communications [13], can be thought of as a special case of spread spectrum. Each individual bit can, in theory, occupy a bandwidth of several gigahertz. This makes a hostile detection very complicated and gives very efficient multipath rejection characteristics. The synchronization requirements are very severe—not in terms of carrier frequency, because there is none—but regarding the baseband timing. Again, there is no reason to separately transfer the clock pattern across the air interface. Some reports of scientific experiments suggest pulse widths down to about 50 ps. A wideband data communication capability seems to require timing uncertainties below this, which can be quite difficult to achieve in a mobile radio device regardless of technology.

7.2.2.6 Frequency Tracking Through the Air Interface

The invention of practical PLL circuits made it possible to start experiments with a real-time frequency and timing control over the air interface whereby radio terminals can theoretically show performance equal to their cable-connected counterparts, (see, for example, [14]). The first widespread implementations of this method were introduced as automatic frequency correction (AFC) circuits in simple FM receivers. Currently the need for frequency and code tracking is partly based on the Doppler cancellation and partly on the requirement of highest data rates. Intelligent DSP blocks can be utilized to combine both functions on single chip.

The problems of synchronization through the mobile radio interface are twofold. First of all, the carrier-to-noise ratio is typically far less than in cable networks. This sets considerable requirements to the adaptive filtering functions, normally installed in the DSP chip. Second, the delay stability and pulse train integrity of the detected base band signal is often questionable. This can often not be overcome just by algorithmic processing but might require supporting hardware in the form of local high stability oscillators.

References

[1] ITU-T Recommendation, “Physical/Electrical Characteristics of Hierarchical Digital Interfaces,” G.703, 2001.

[2] ITU-T Recommendation, “Optical Interfaces for Equipments and Systems Relating to the Synchronous Digital Hierarchy,” G.957, 1999.

[3] ITU-T Recommendation, “Network Node Interface for the Synchronous Digital Hierarchy (SDH),” G.707, 2000.

[4] Clock synthesizer, Lucent Technologies, TTRN012G5 (2.5Gbit/s).

[5] Clock synthesizer, Lucent Technologies, TTRN01110G.

[6] ITU-T Recommendation, "Timing Characteristics of Primary Reference Clocks," G.811, 1997.

[7] ITU-T Recommendation, "Timing Requirements of Slave Clocks Suitable for Use as Node Clocks in Synchronization Networks," G.812, 1998.

[8] ITU-T Recommendation, "Timing Characteristics of SDH Equipment Slave Clocks (SEC)," G.813, 1996.

[9] Norbert, G., and W. Wiesbeck, *Planungsmethoden für die Mobilkommunikation*, Heidelberg: Springer Verlag, 1998.

[10] Kadish, J., and T. East, *Satellite Communication Fundamentals*, Norwood, MA: Artech House, 2000.

[11] Dambacher, P., *Digital Terrestrial Television Broadcasting*, Heidelberg: Springer Verlag, 1998.

[12] Trenkle, F., *Die deutschen Funkstörverfahren bis 1945*, Ulm: AEG-Telefunken, 1984.

[13] Vakin, S., L. Shustov, and R. Dunwell, *Fundamentals of Electronic Warfare*, Norwood, MA: Artech House, 2001.

[14] Eskelinen, P., "Experiments with a Caesium-Locked UHF Time and Frequency Reference Transmitter," *Proc. 14th European Time and Frequency Forum*, Turin, 2000, pp. 204–208.