Orthogonal Frequency Division Multiple Access

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- 1. Orthogonal Frequency Division Multiplexing
- 2. OFDMA in a Mobile Cellular Network
- 3. Single Carrier Frequency Division Multiple Access

- Orthogonal Frequency Division Multiple Access (OFDMA)
    - ✓ The technique used for radio transmission and reception in LTE
    - ✓ Carries out the same functions as any other multiple access technique, by allowing the BS to communicate with <u>several different mobiles</u> at the same time
    - ✓ A powerful way to <u>minimize</u> the problems of <u>fading</u> and <u>inter-symbol interference</u>

- OFDMA is used by several other radio communication systems
  - ✓ IEEE 802.11 versions a, g and n
  - ✓ WiMAX (IEEE 802.16)
  - ✓ Digital television
  - ✓ Radio broadcasting

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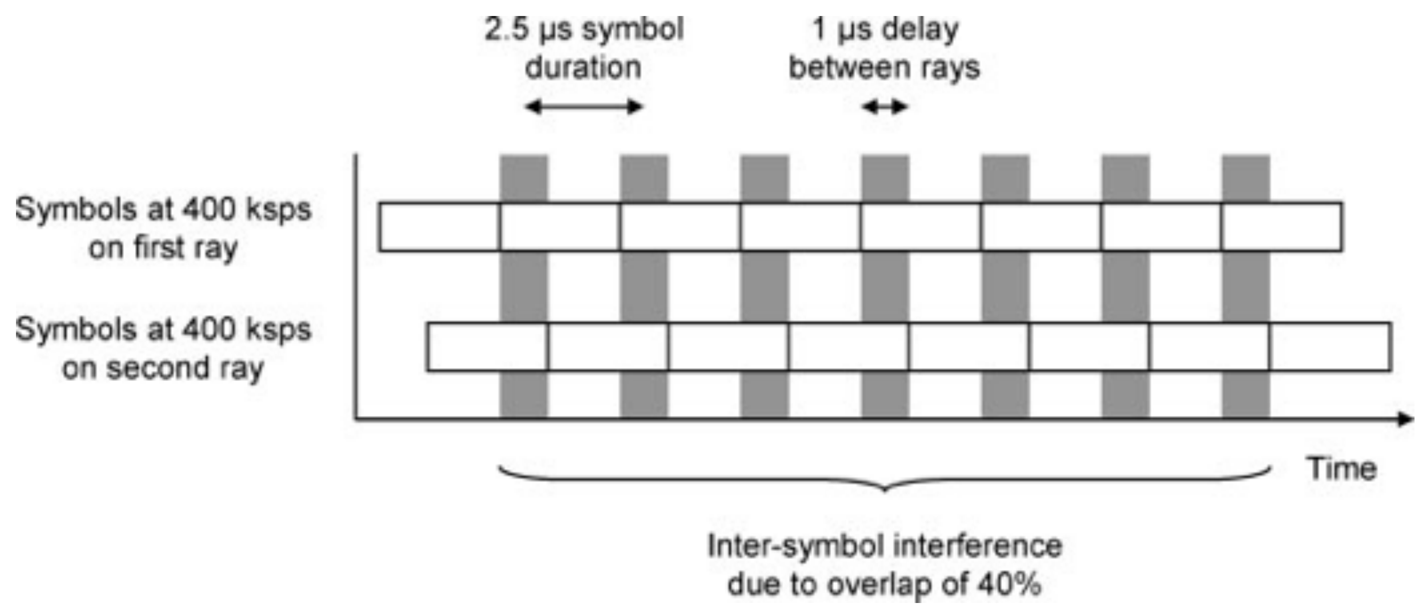
1. Orthogonal Frequency Division Multiplexing

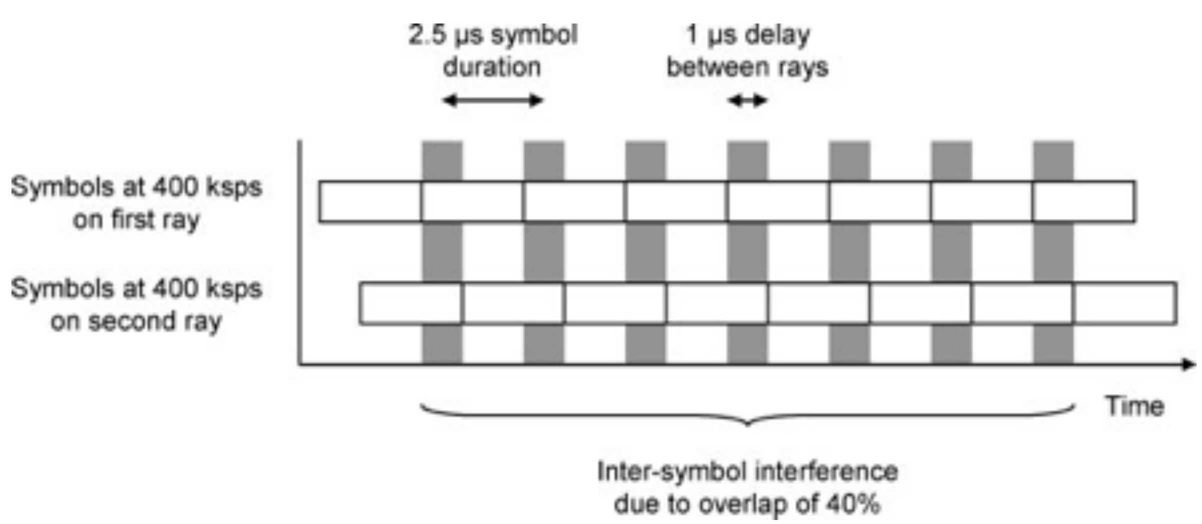
- 1.1 Reduction of Inter-Symbol Interference using OFDM
- 1.2 The OFDM Transmitter
- 1.3 Initial Block Diagram

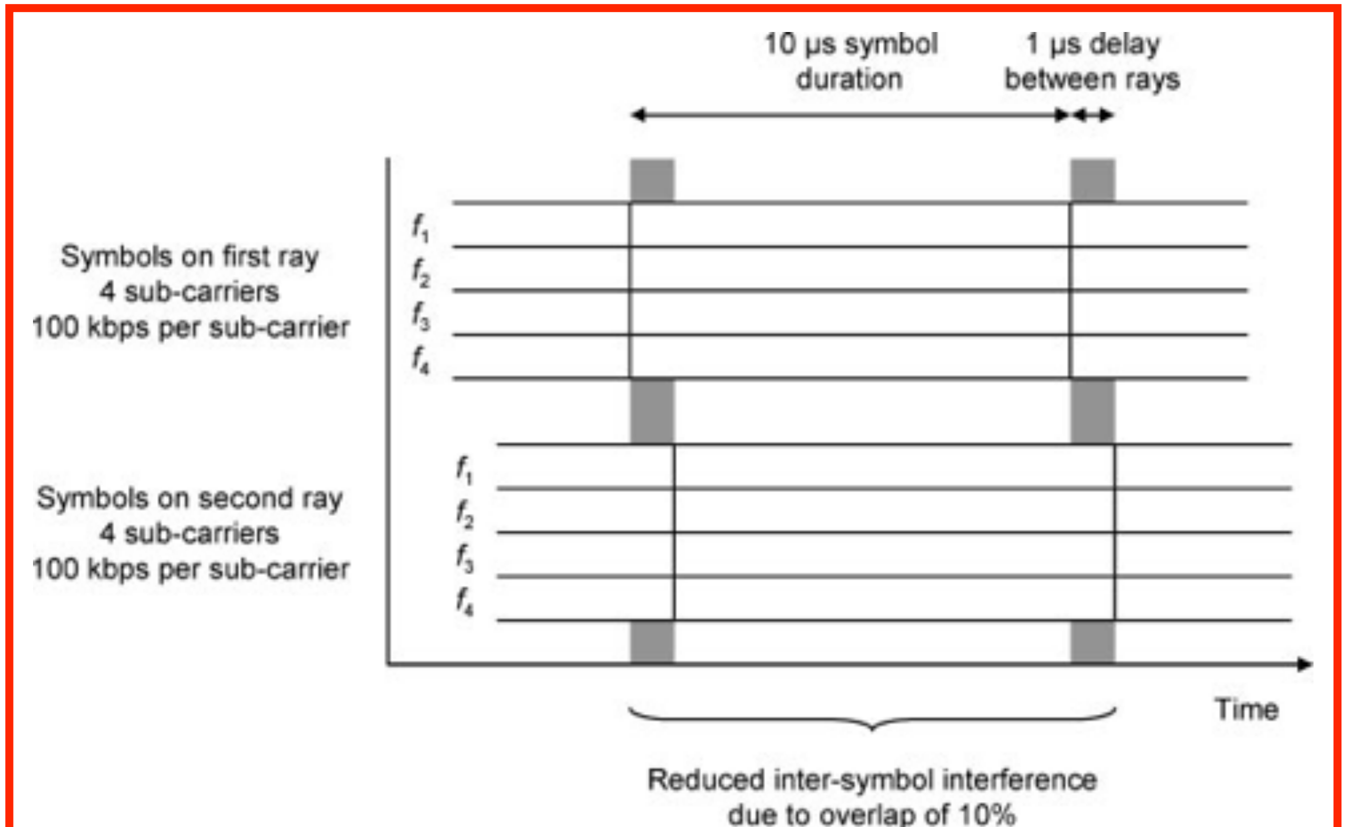
1.1 Reduction of Inter-Symbol Interference using OFDM

- High data rate transmission in a multipath environment leads to Inter Symbol Interference (ISI)
  - ✓ Example, the delay spread was $1\mu s$ and the data rate was 400 ksps, so the symbols overlapped at the receiver by 40%
  - ✓ This led to <u>interference</u> and <u>bit errors</u> at the receiver
  - ✓ OFDM is a powerful way to solve the problem



- OFDM transmitter
  - ✓ Divides the information into several parallel sub-streams
  - ✓ Sends each sub-stream on a different frequency (sub-carrier)
    - If the total data rate stays the same, then
      - The data rate on each sub-carrier is less than before, so the symbol duration is longer
    - This reduces the amount of ISI, and reduces the error rate





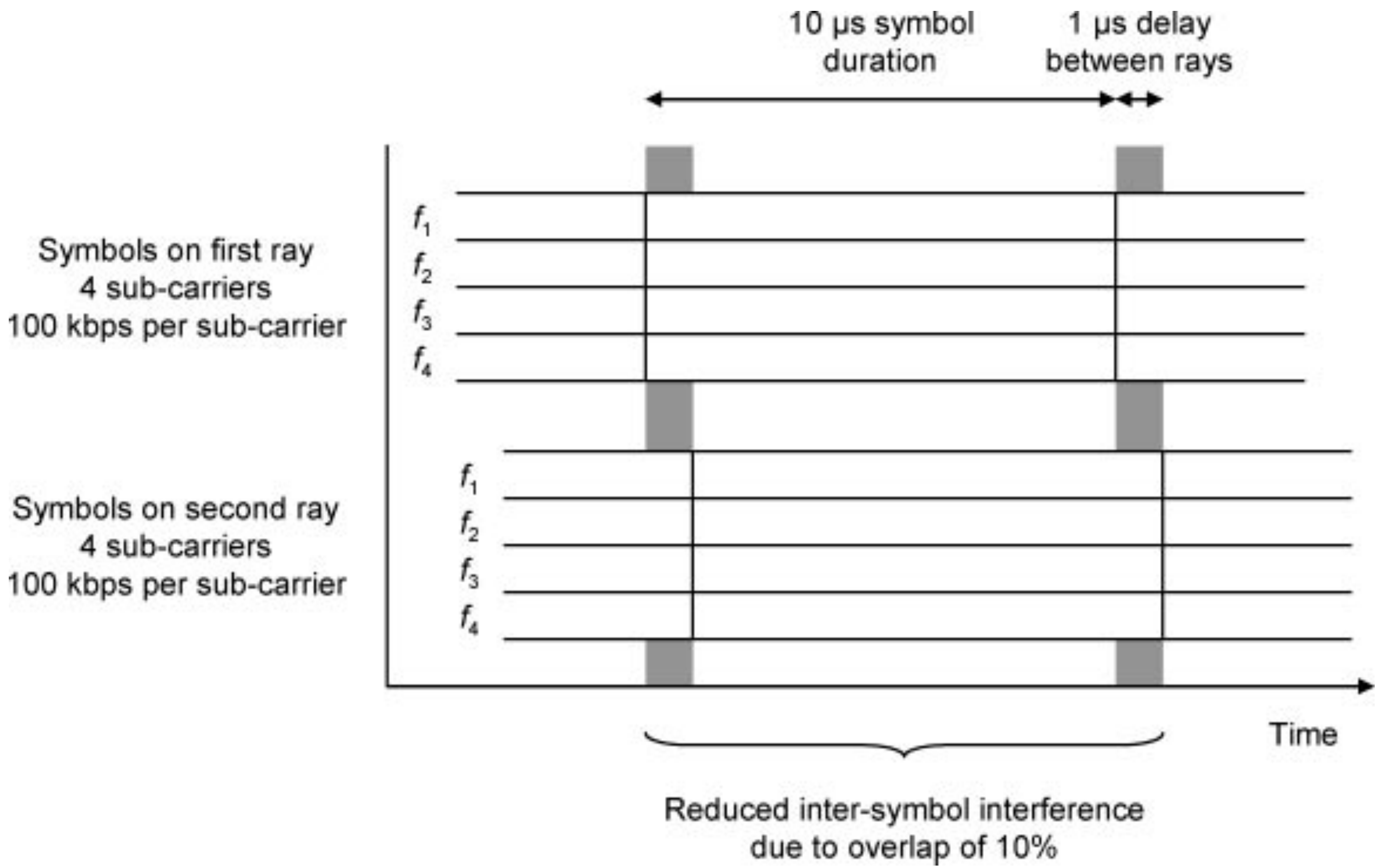
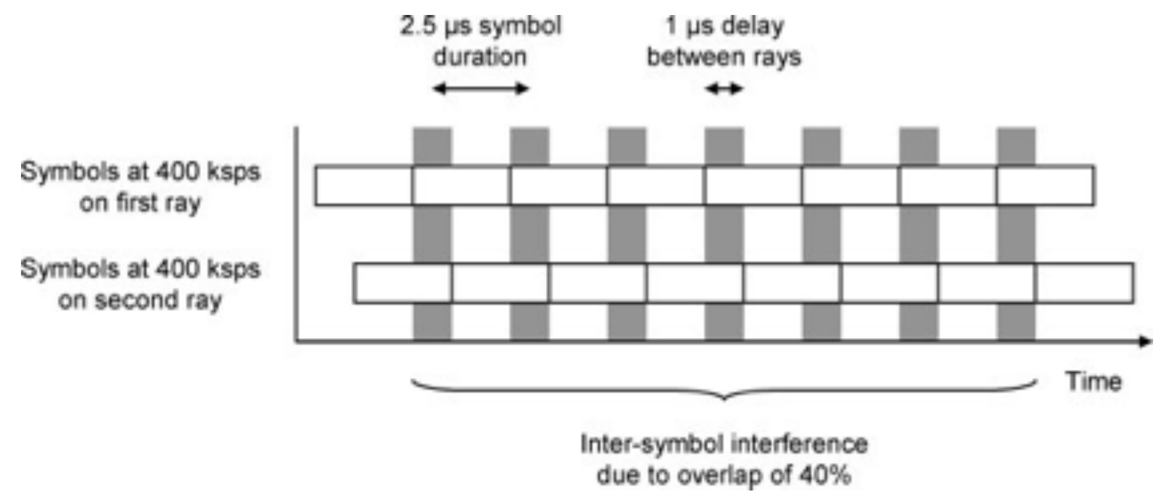
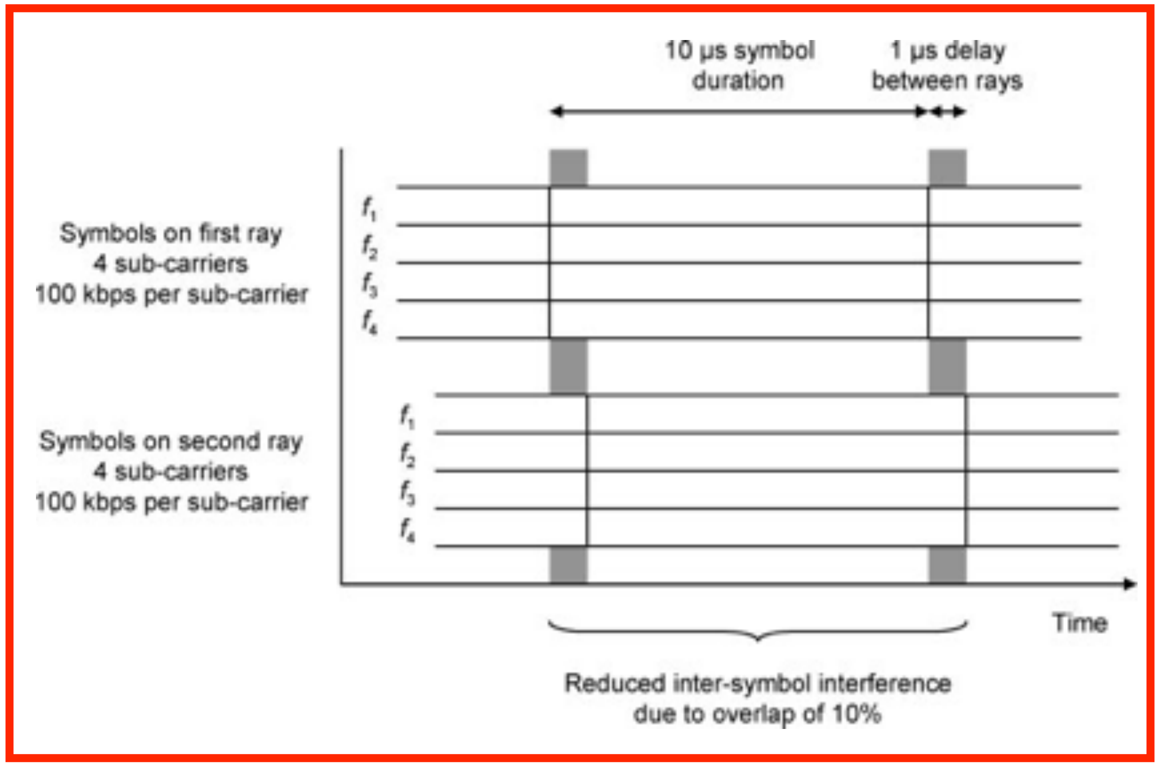


Figure 4.1 Reduction of inter-symbol interference by transmission on multiple sub-carriers.

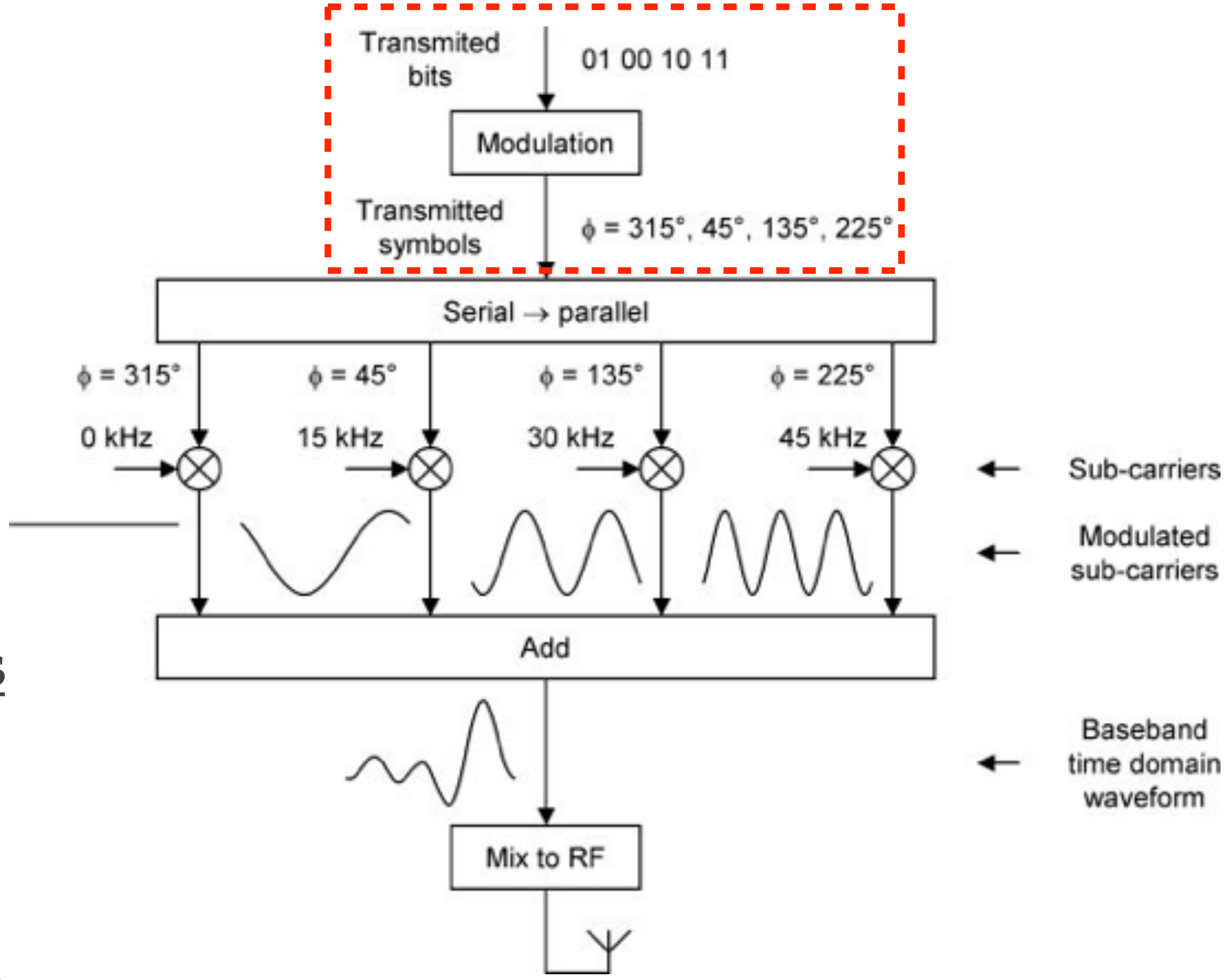
- Figure 4.1
  - ✓ Divid the original data stream amongst four sub-carriers with frequencies f_1 to f_4
  - ✓ The data rate on each sub-carrier is now 100 ksps, so the symbol duration has increased to 10μs
  - ✓ If the delay spread remains at 1μs, then the symbols only overlap by 10%
  - ✓ This reduces the amount of ISI to one quarter of what it was before and reduces the number of errors in the receiver
- LTE can use a very large number of sub-carriers, up to a maximum of 1200 in Release 8, which reduces the amount of ISI to negligible levels





1.2 The OFDM Transmitter

- Figure 4.2 is a block diagram of an analogue OFDM transmitter
- Transmitter
  - ✓ Accepts a stream of bits from higher layer protocols, and
  - ✓ Converts them to symbols using the chosen modulation scheme, for example quadrature phase shift keying (QPSK)



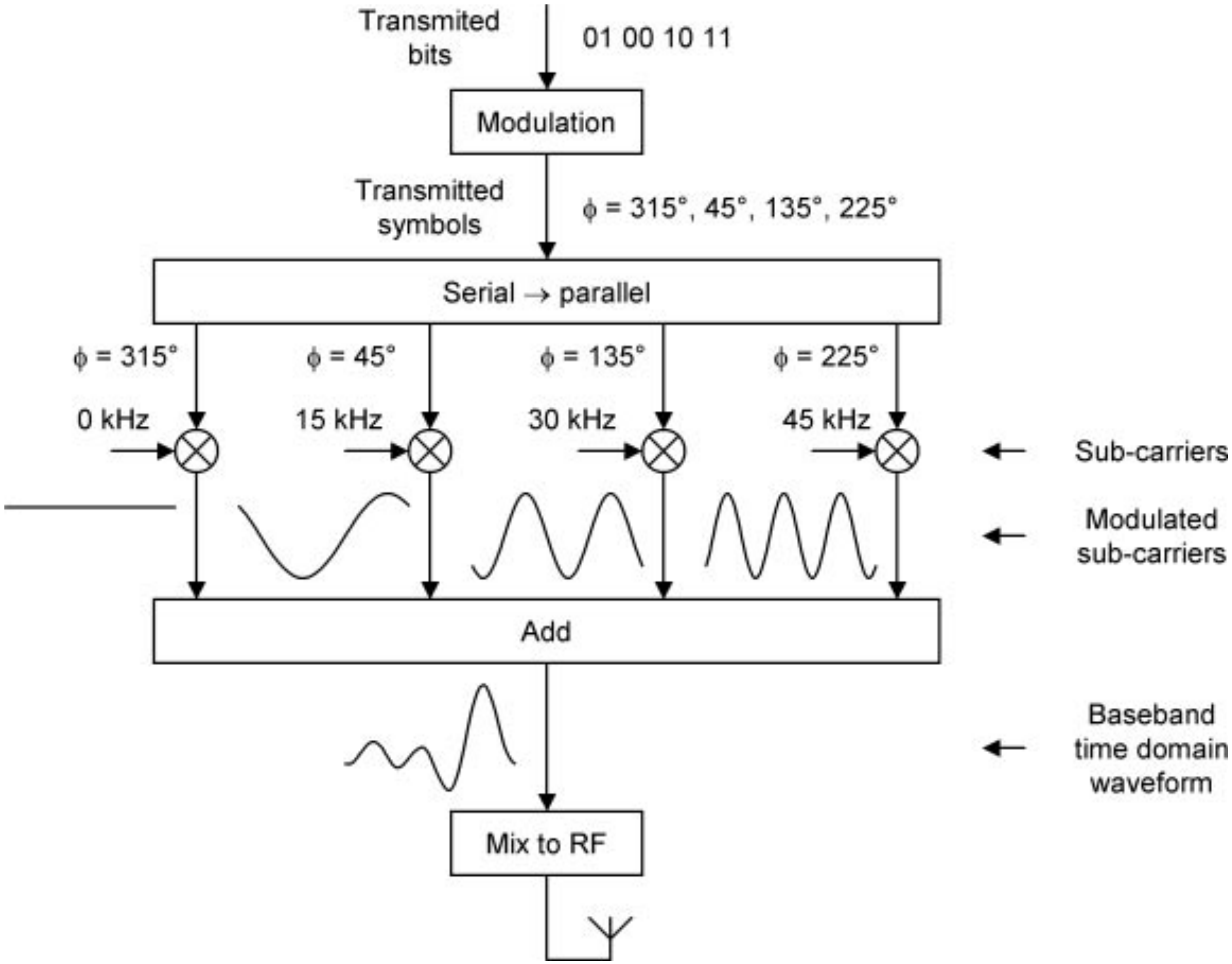
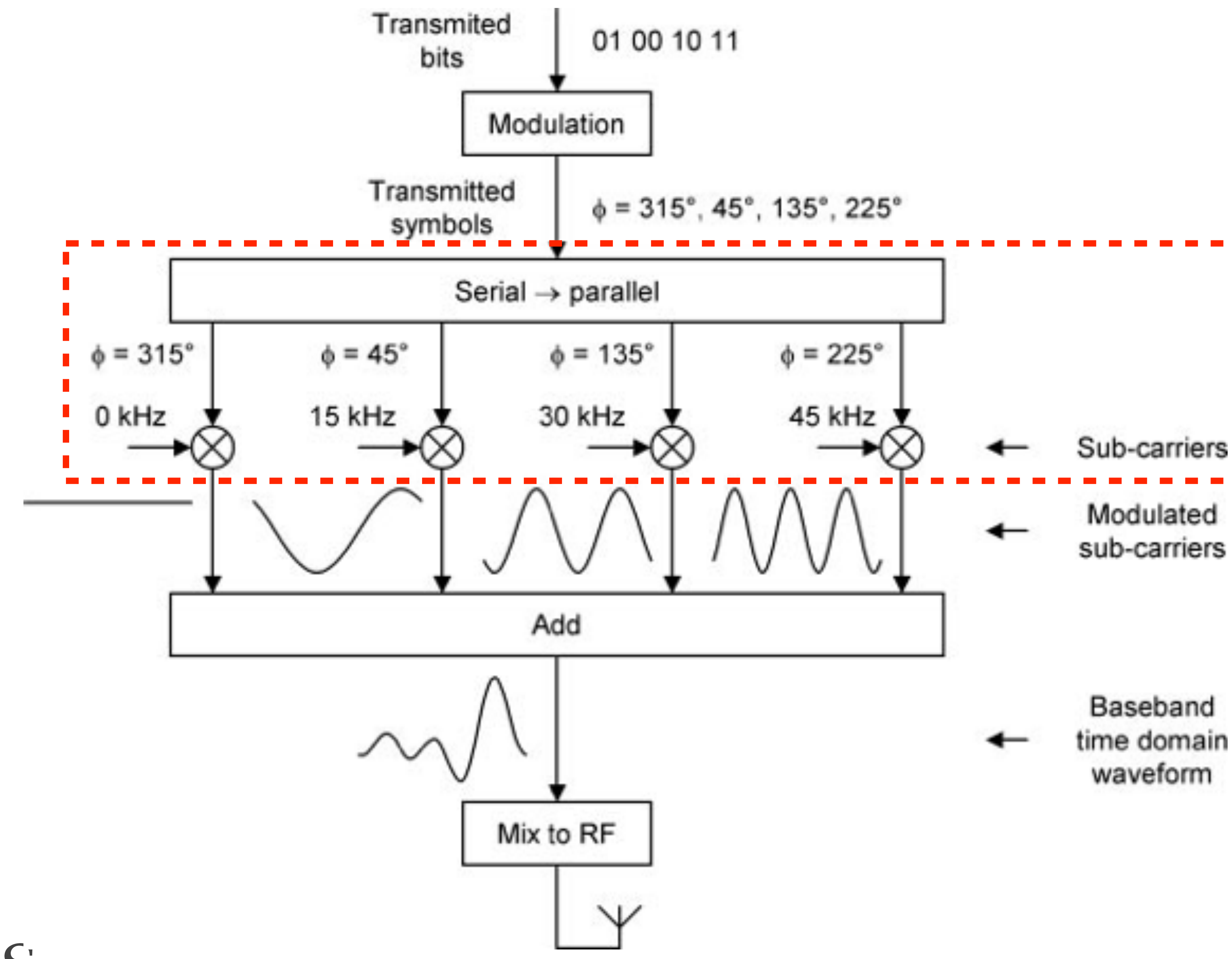
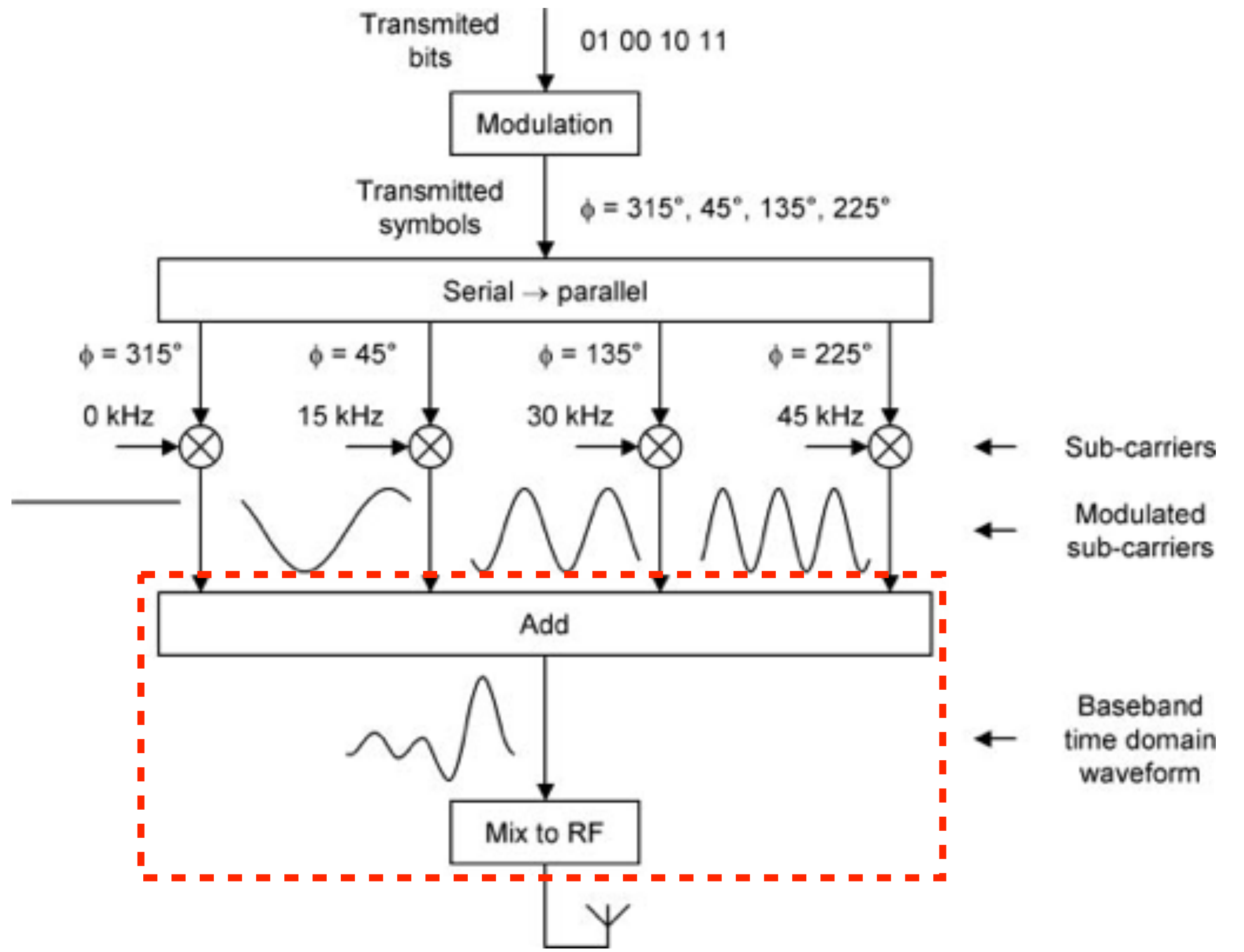


Figure 4.2 Processing steps in a simplified analogue OFDM transmitter.

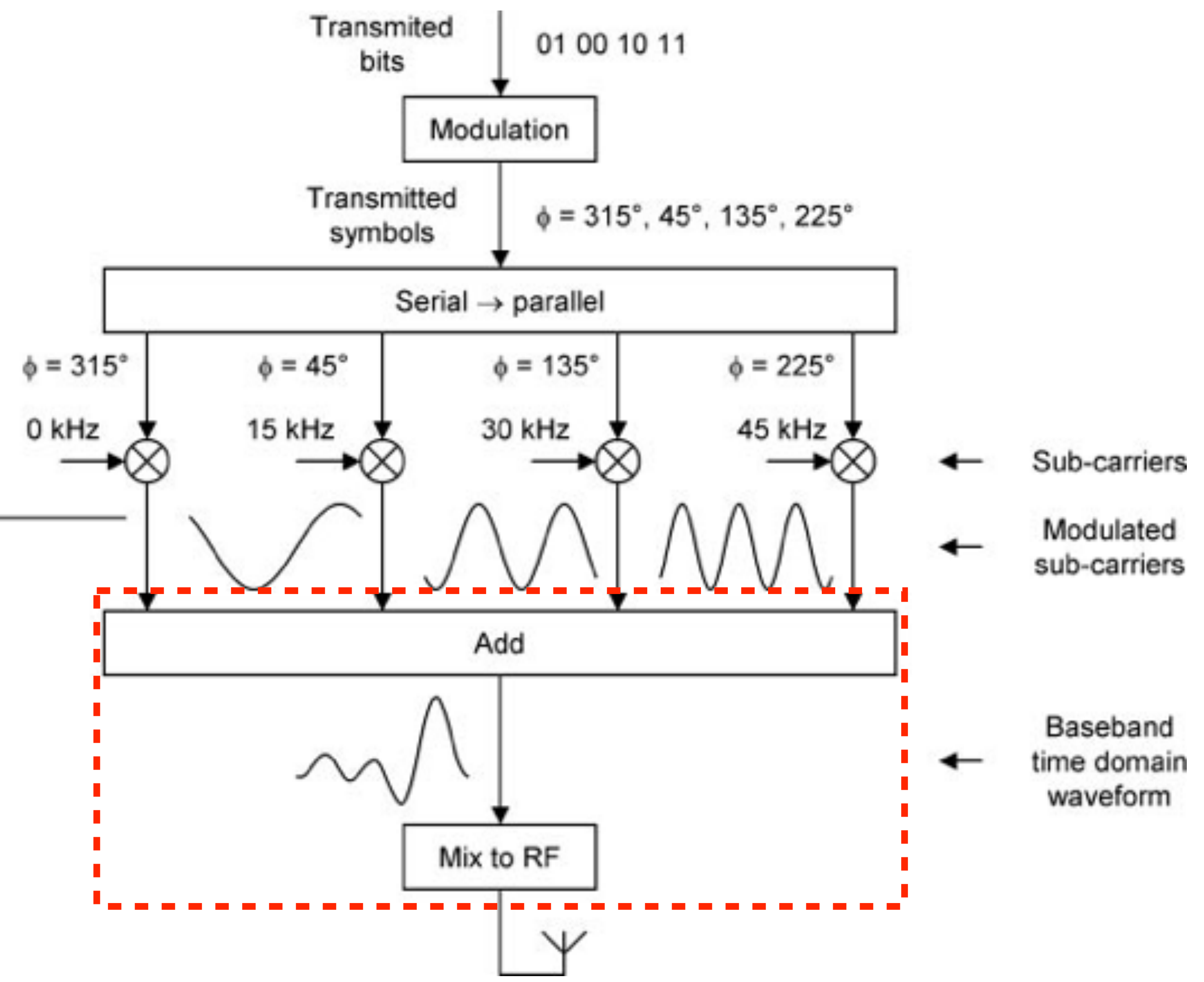
- Serial-to-parallel converter
  - ✓ Takes a block of symbols, four in this example
  - ✓ Mixes each symbol with one of the sub-carriers by adjusting its amplitude and phase



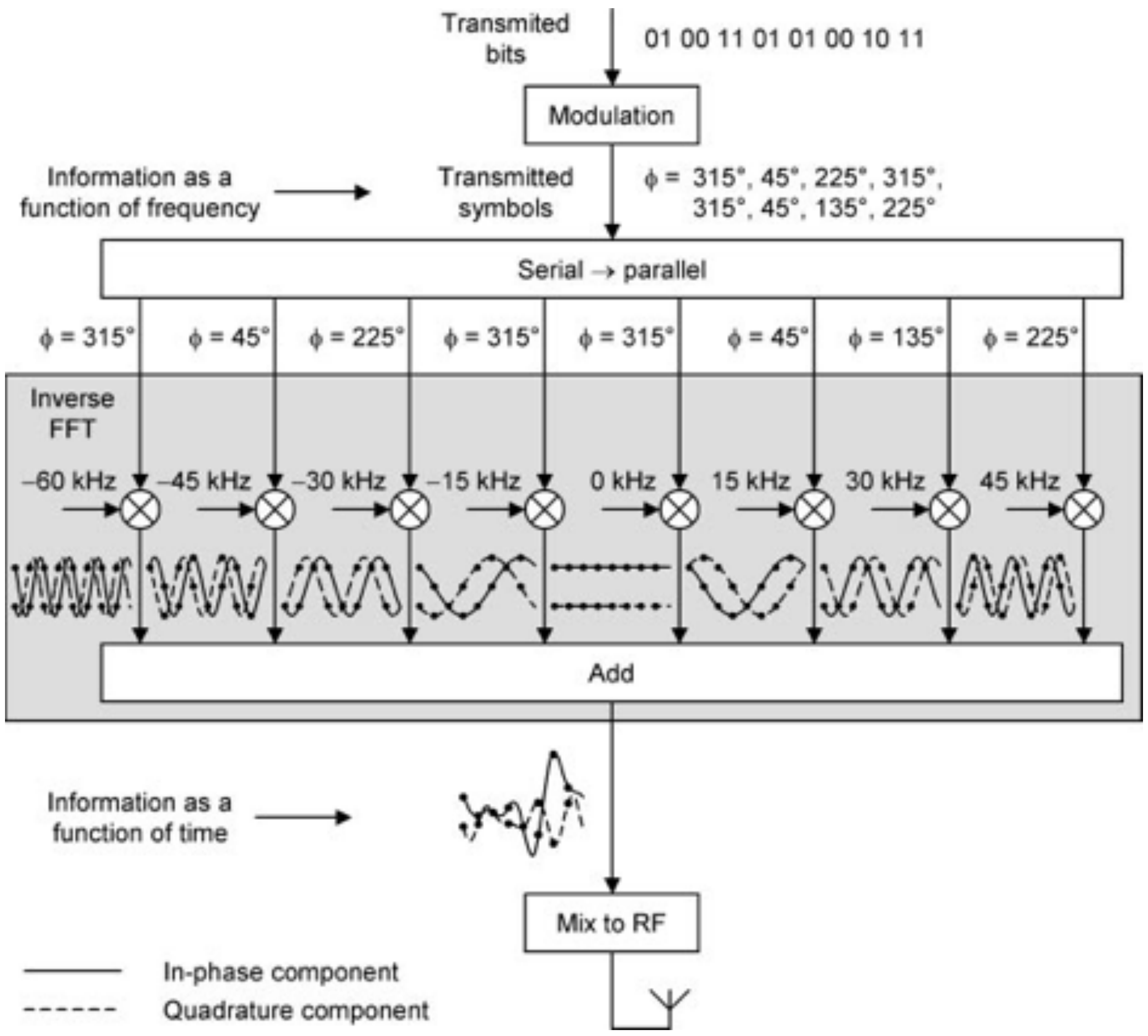
- LTE uses a fixed sub-carrier spacing of 15 kHz, so the sub-carriers in Figure 4.2 have frequencies of 0, 15, 30 and 45 kHz. (Mix the signals up to radio frequency (RF) at the end)
- The symbol duration is the reciprocal of the sub-carrier spacing, so is about 66.7μs
  - ✓ 15 kHz, 30 kHz, and 45 kHz sub-carriers goes through one, two and three cycles during the 66.7 μs symbol duration, respectively



- We now have <u>four sine waves</u>, at <u>frequencies</u> of 0, 15, 30 and 45 kHz, whose <u>amplitudes</u> and <u>phases</u> represent the eight transmitted bits (01 00 10 11)
- By <u>adding</u> these sine waves together, we can generate a <u>single **time-domain waveform**</u>, which is a <u>low frequency representation</u> of the signal that we need to <u>send</u>
- Finally, <u>mix</u> the waveform up to radio frequency (RF) for transmission



- Figure 4.3 includes three extensions
  - ✓ (1) Add four more sub-carriers, at frequencies of −15, −30, −45 and −60 kHz
    - The distinction between positive and negative frequencies is that the latter are eventually transmitted below the carrier frequency, not above it
    - At a carrier frequency of 800 MHz, for example, the 15 kHz sub-carrier ends up at 800.015 MHz, while the −15 kHz sub-carrier ends up at 799.985 MHz



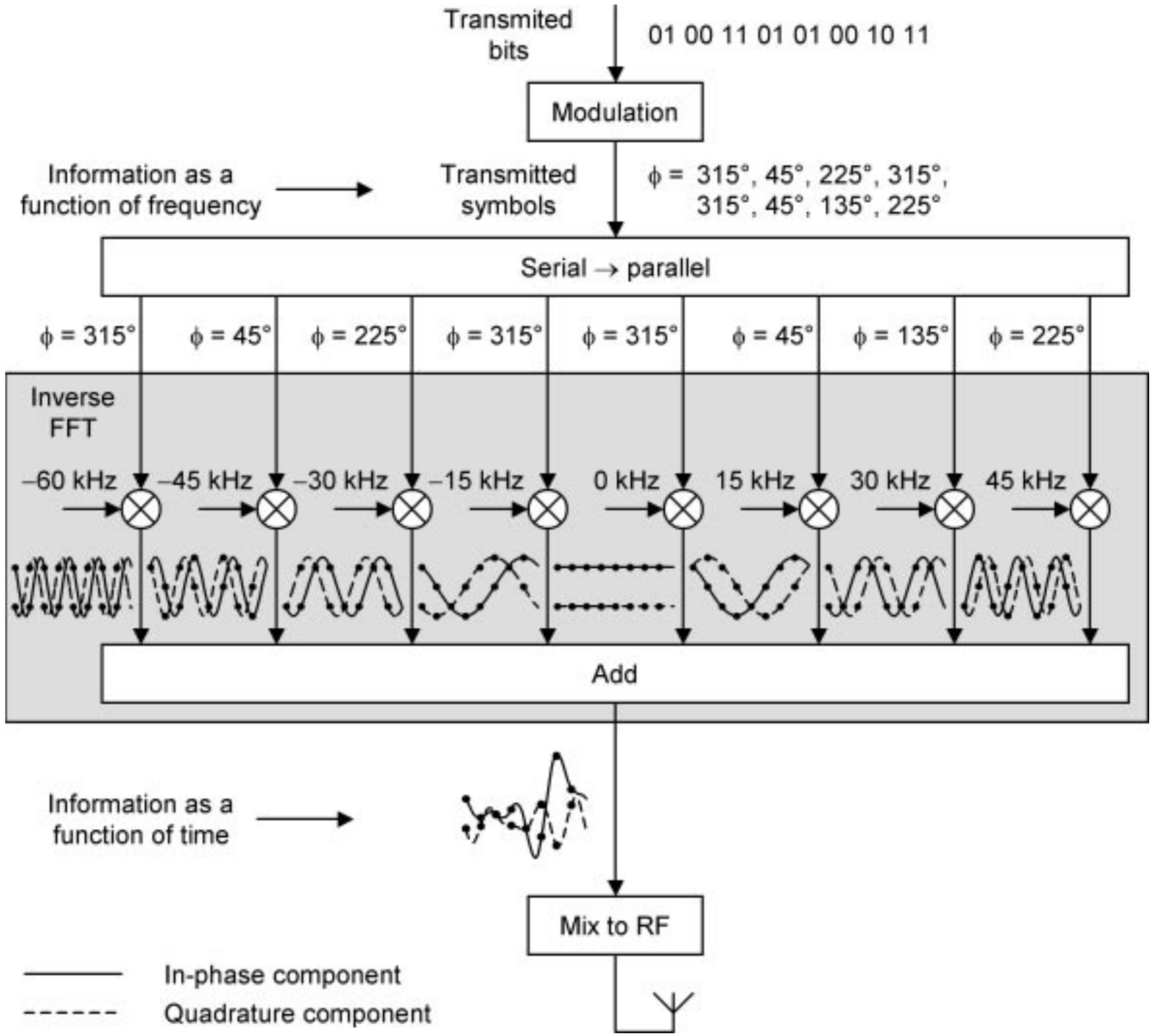
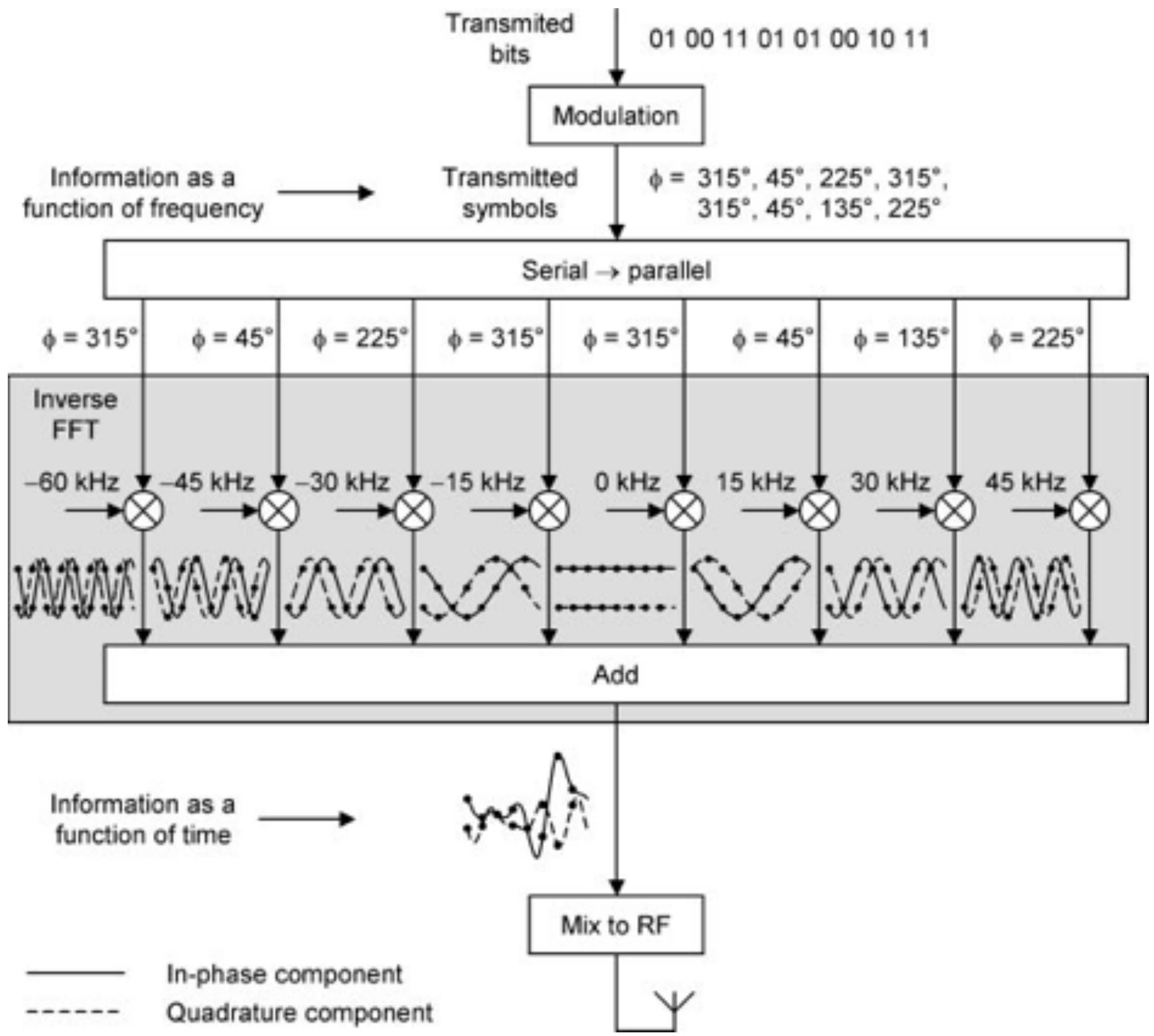
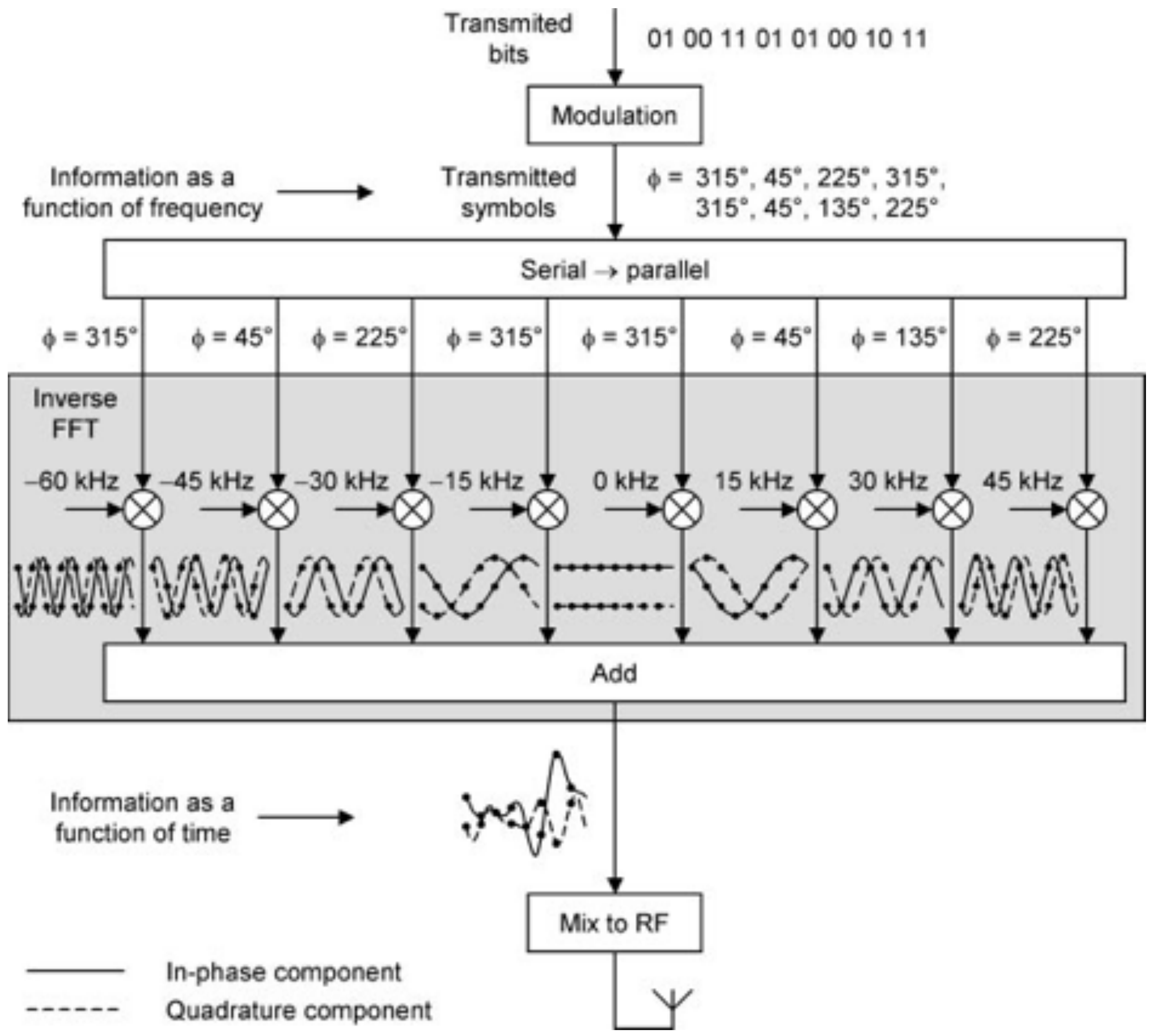


Figure 4.3 Processing steps in a digital OFDM transmitter.

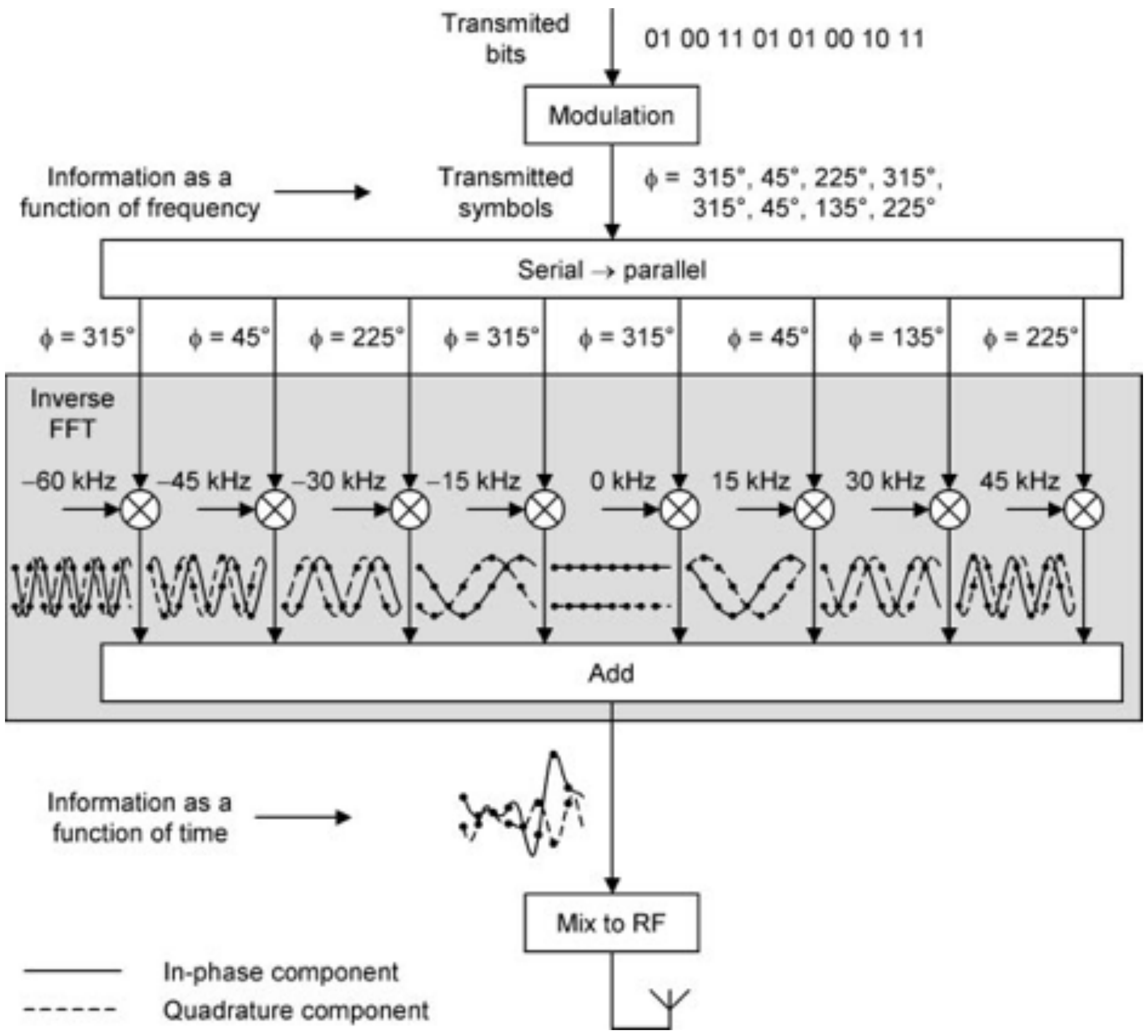
- (2) Distinguish the positive and negative frequencies by retaining the in-phase and quadrature components of each sub-carrier through most of the transmission process
  - In Figure 4.3, for example, the in-phase components of the 15 kHz and –15 kHz signals are exactly the same, but we can distinguish them because their quadrature components are different
  - After mixing the information up to radio frequency, all the frequencies are positive and the quadrature components can be discarded



- (3) It is highly desirable to do the processing digitally, rather than in analogue form
  - In Figure 4.3, we sample the in-phase and quadrature components eight times per symbol, which allows us to sample the −60 kHz sub-carrier twice in every cycle
  - More generally, the minimum number of samples per symbol equals the number of sub-carriers
  - We can then do the mixing and addition operations digitally, which results in a digital time-domain waveform that contains all the information we require
  - We can then convert the waveform from digital to analogue form, filter it and mix it up to radio frequency for transmission



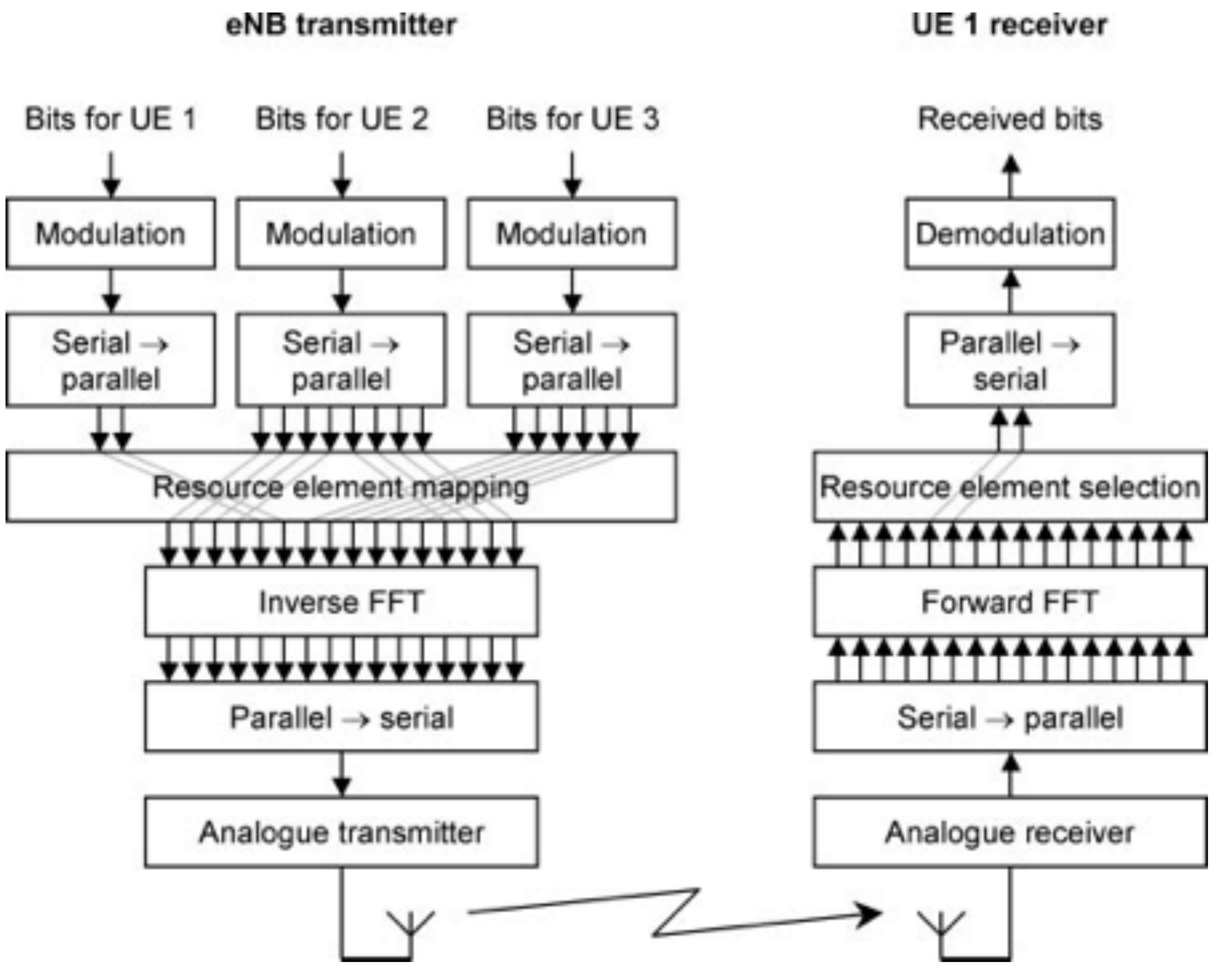
- Two important points in the processing chain
  - ✓ Serial-to-parallel conversion stage
    - The data represent the amplitude and phase of each sub-carrier, as a function of frequency
  - ✓ After the addition stage towards the end
    - The data represent the in-phase and quadrature components of the transmitted signal, as a function of time
  - ✓ The mixing and addition steps have simply converted the data from a function of frequency to a function of time



- This conversion is called the inverse discrete Fourier transform (DFT)
  - ✓ The Fourier transform converts data from the time domain to the frequency domain, so the transmitter requires an inverse transform, which carries out the reverse process
- In turn, the discrete Fourier transform can be implemented extremely quickly using fast Fourier transform (FFT)
  - ✓ This limits the computational load on the transmitter and receiver, and allows the two devices to be implemented in a computationally efficient way
  - ✓ However, there is one important restriction
    - For the FFT to work efficiently, the number of data points should be either an exact power of two or a product of small prime numbers alone

1.3 Initial Block Diagram

- Figure 4.4 is a block diagram of an OFDM transmitter and receiver
- Assume that the system is operating on the downlink, so that the transmitter is in the BS and the receiver is in the mobile



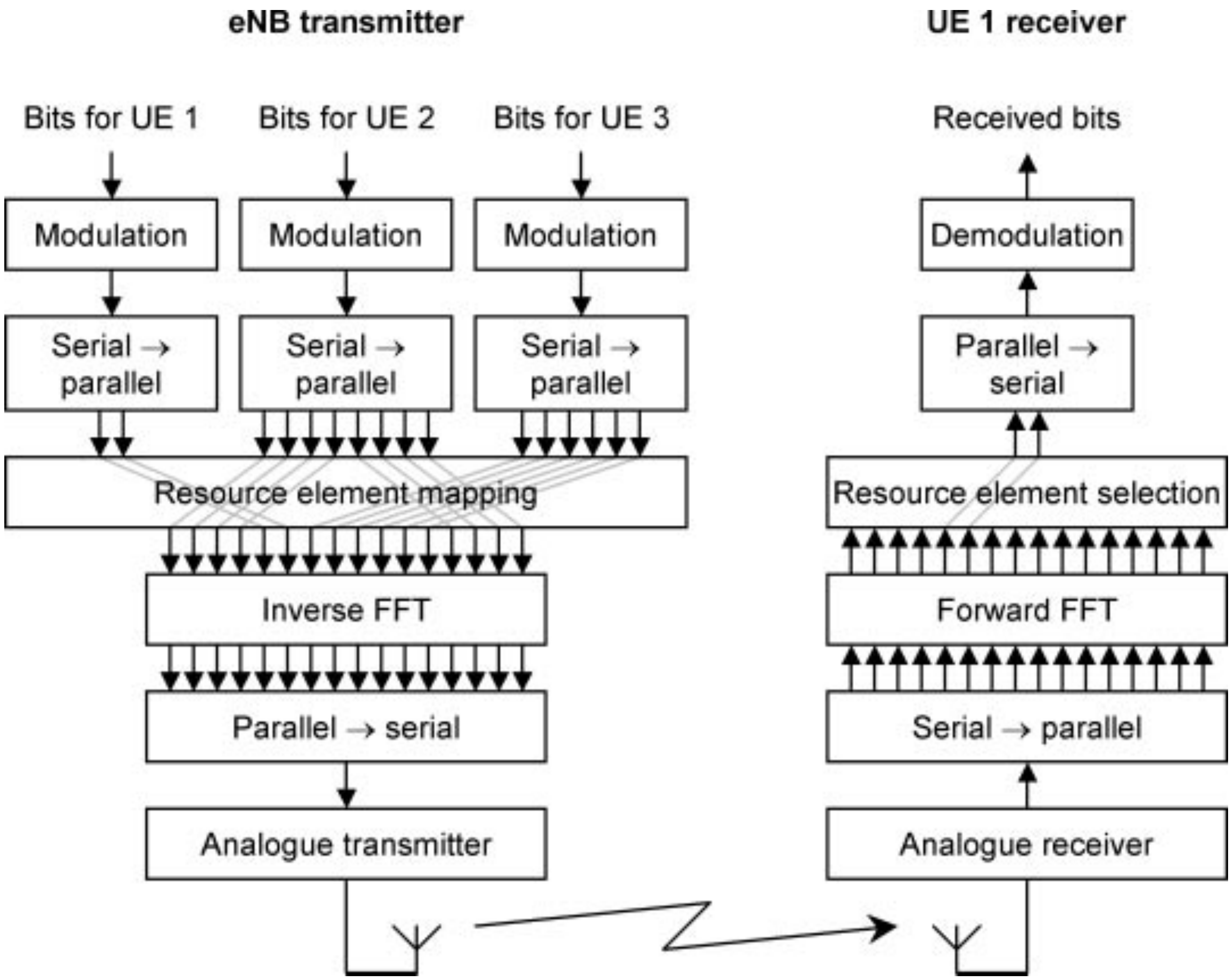
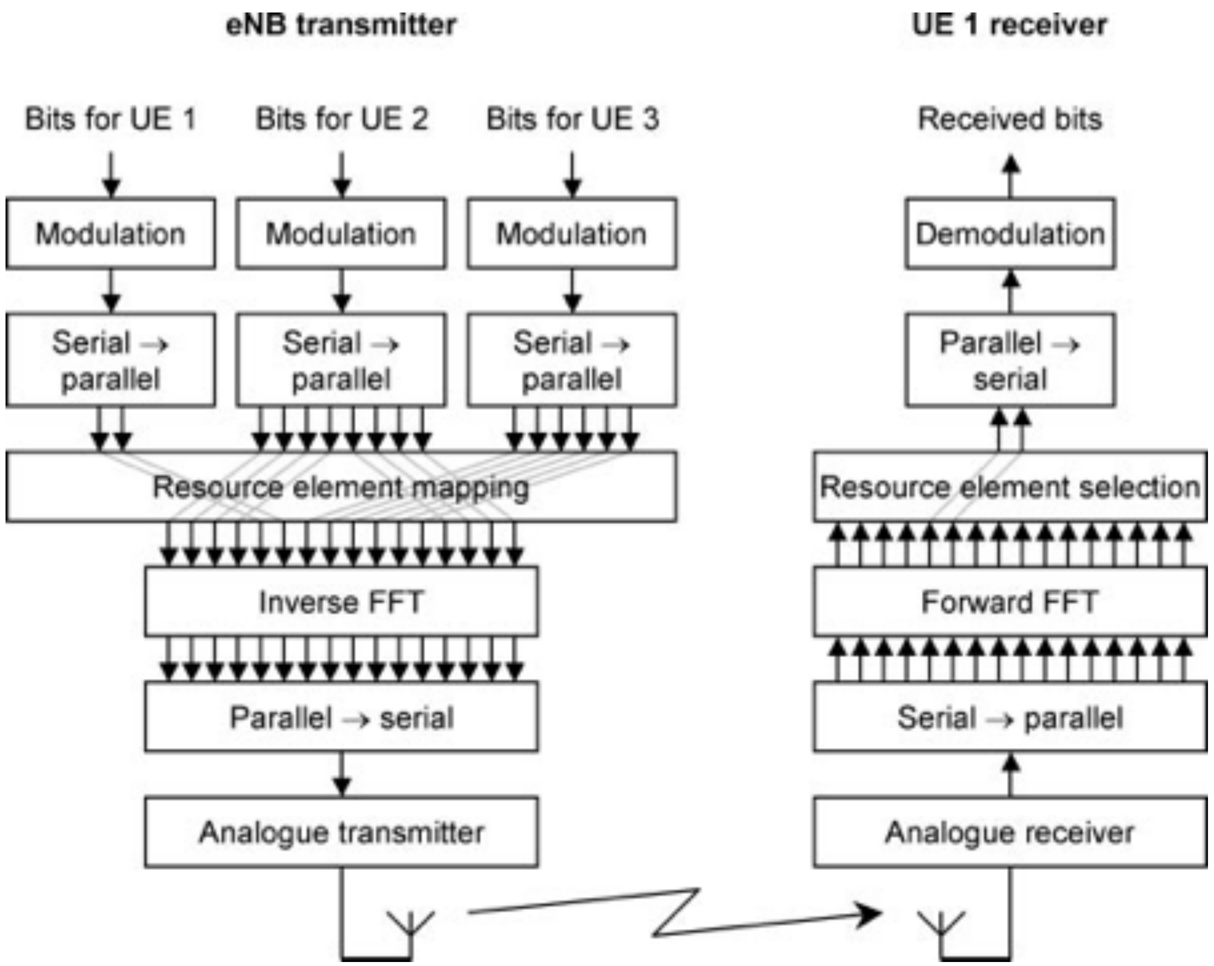
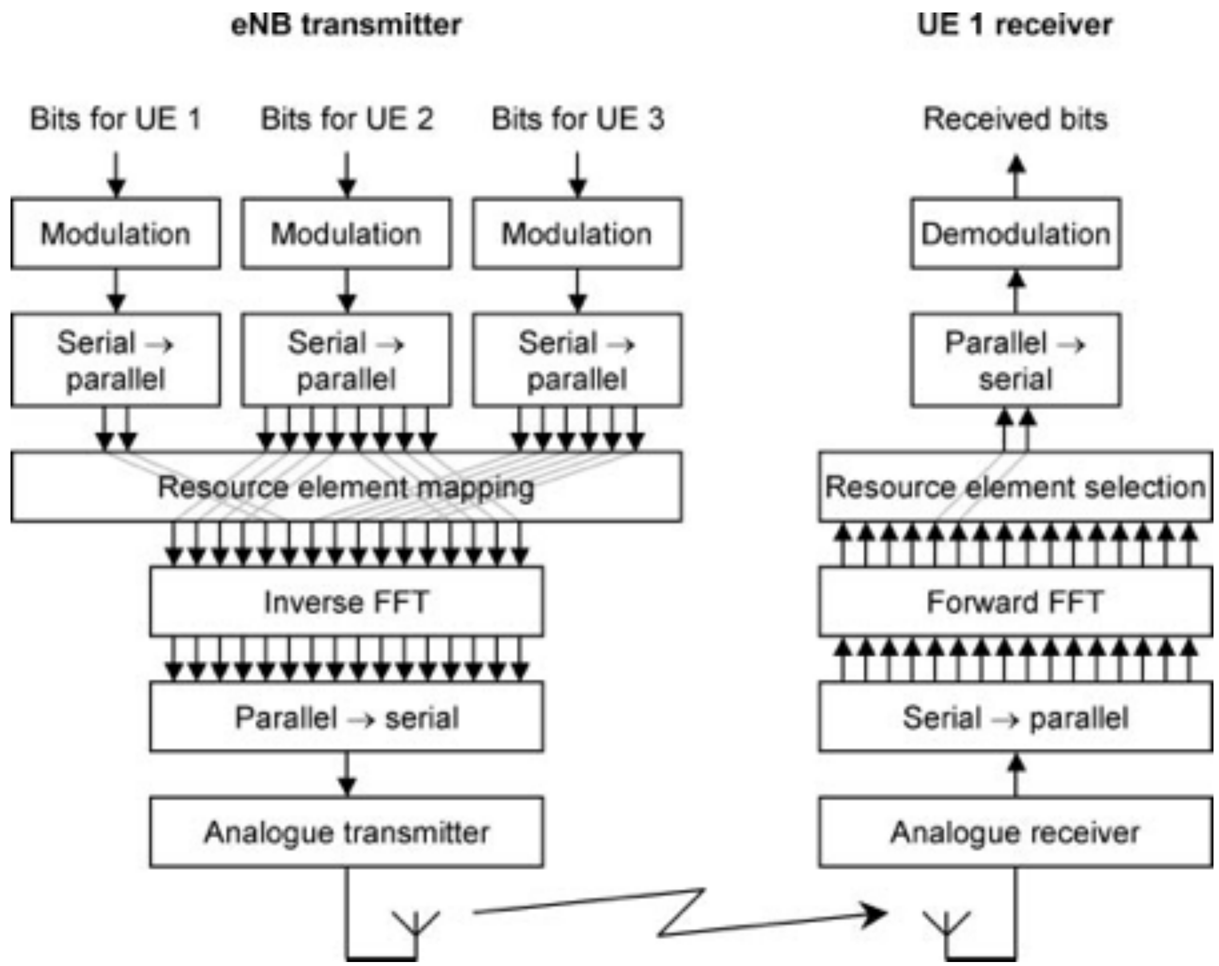


Figure 4.4 Initial block diagram of an OFDM transmitter and receiver.

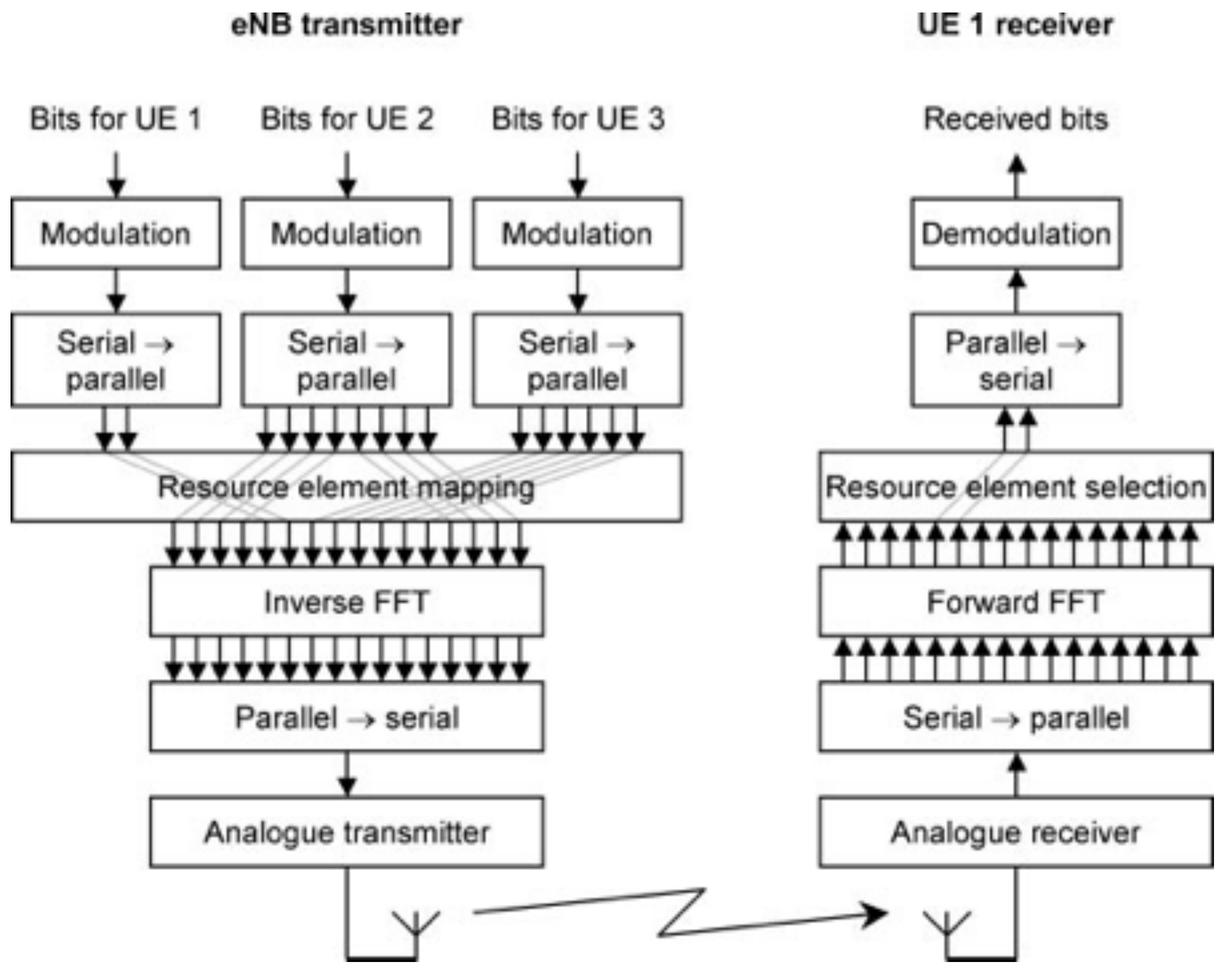
- In the diagram, the BS is sending streams of bits to three different mobiles
- It modulates each bit stream independently, possibly using a different modulation scheme for each one
- It then passes each symbol stream through a serial-to-parallel converter, to divide it into sub-streams
- The num of sub-streams per mobile depends on the data rate
  - ✓ A voice application might only use a few sub-streams
  - ✓ A video application might use many more



- The resource element mapper takes the individual sub-streams and chooses the subcarriers on which to transmit them
- A mobile's sub-carriers may lie in one contiguous block (as in the case of mobiles 1 and 3), or they may be divided (as for mobile 2)
- The resulting information is the amplitude and phase of each sub-carrier as a function of frequency
- By passing it through an inverse FFT, we can compute the in-phase and quadrature components of the corresponding time-domain waveform
- This can then be digitized, filtered and mixed up to radio frequency for transmission



- The mobile reverses the process
    - ✓ Starts by sampling the incoming signal, filtering it, and converting it down to baseband
    - ✓ Passes the data through a forward FFT, to recover the amplitude and phase of each sub-carrier
    - ✓ Assume that the BS has already told the mobile which sub-carriers to use
        - Using this knowledge, the mobile
            - Selects the required sub-carriers
            - Recovers the transmitted information
            - Discarding the remainder



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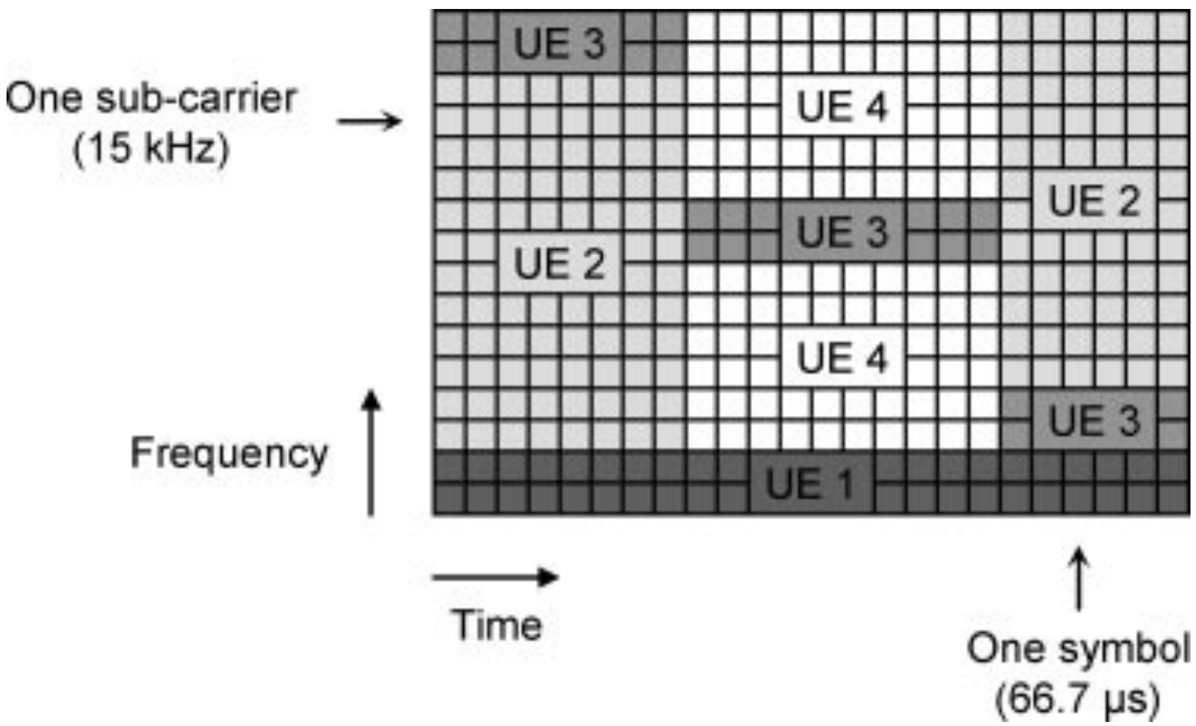
2. OFDMA in a Mobile Cellular Network

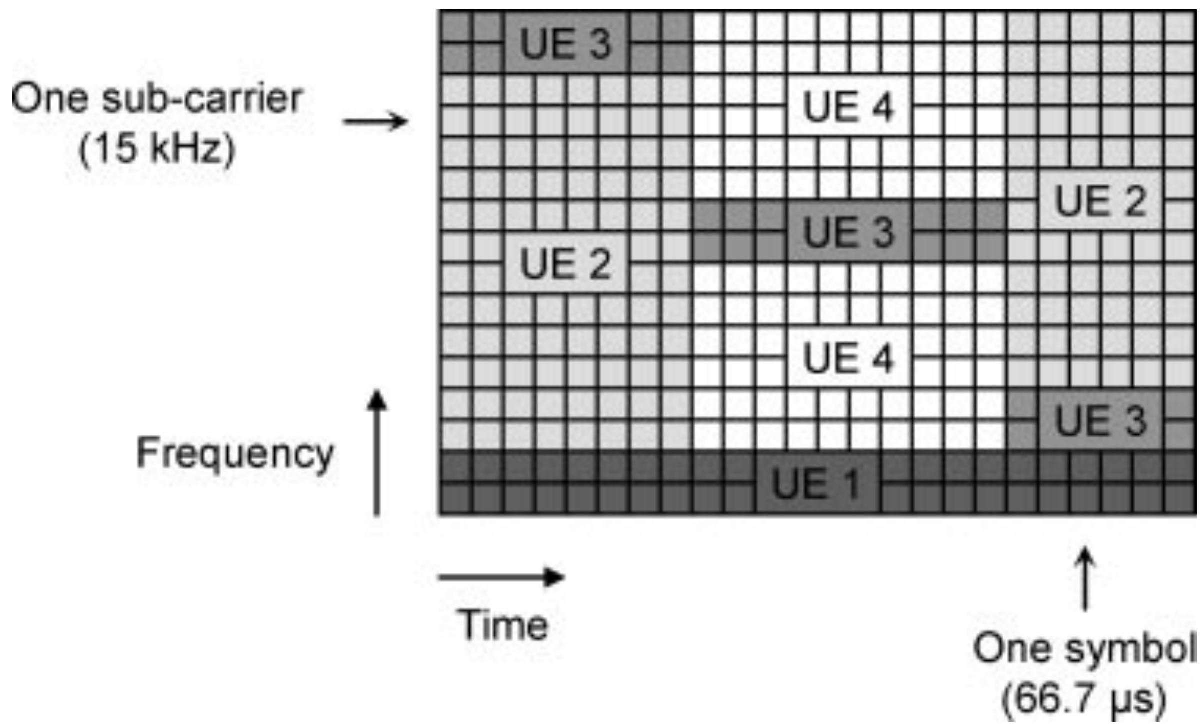
- 2.1 Multiple Access
- 2.2 Fractional Frequency Re-Use
- 2.3 Channel Estimation
- 2.4 Cyclic Prefix Insertion
- 2.5 Use of the Frequency Domain
- 2.6 Choice of Sub-Carrier Spacing

2.1 Multiple Access

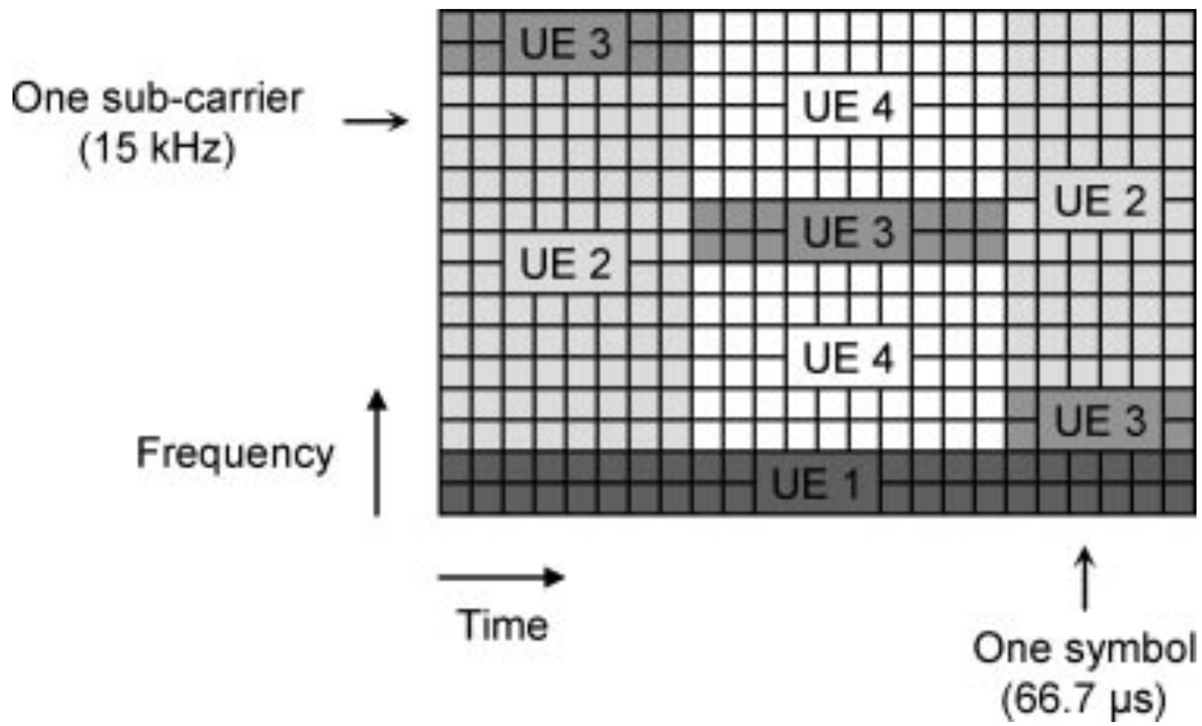
- Orthogonal Frequency Division Multiple Access (OFDMA)
  - ✓ The BS shares its shares its resources by transmitting to the <u>mobiles</u> at <u>different times</u> and <u>frequencies</u>, so as to meet the requirements of the <u>individual applications</u> (Figure 4.5)



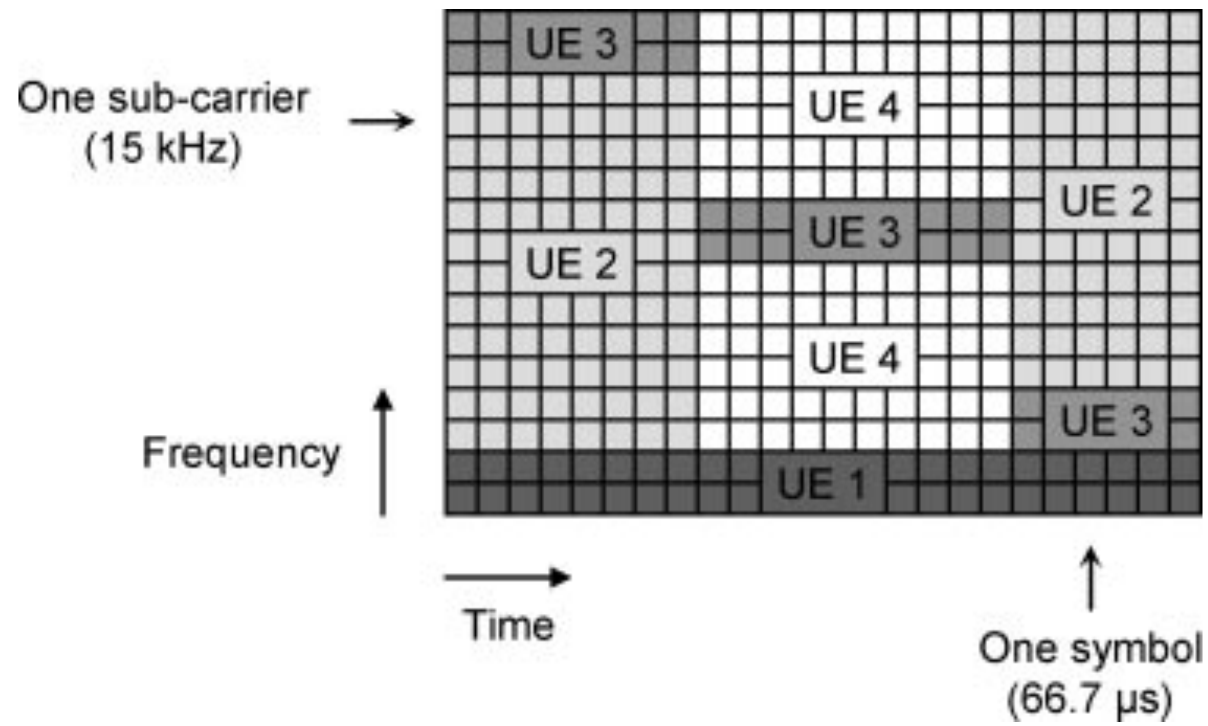
- Example
  - ✓ Mobile 1 is receiving a voice over IP stream, so the data rate, and hence the num of sub-carriers, is low but constant
  - ✓ Mobile 2 is receiving a stream of non real time packet data
  - ✓ The average data rate is higher, but the data come in bursts, so the num of sub-carriers can vary



- The BS can also respond to frequency dependent fading, by allocating subcarriers on which the mobile is receiving a strong signal
    - ✓ In the figure, mobile 3 is receiving a VoIP stream, but it is also affected by frequency dependent fading
    - ✓ In response, the BS allocates sub-carriers on which the mobile is receiving a strong signal, and changes this allocation as the fading pattern changes
    - ✓ In a similar way, it can transmit to mobile 4 using two separate blocks of sub-carriers, which are separated by a fade



- By allocating sub-carriers in response to changes in the fading patterns, an OFDMA transmitter can greatly reduce the impact of time- and frequency-dependent fading
- The process requires feedback from the mobile



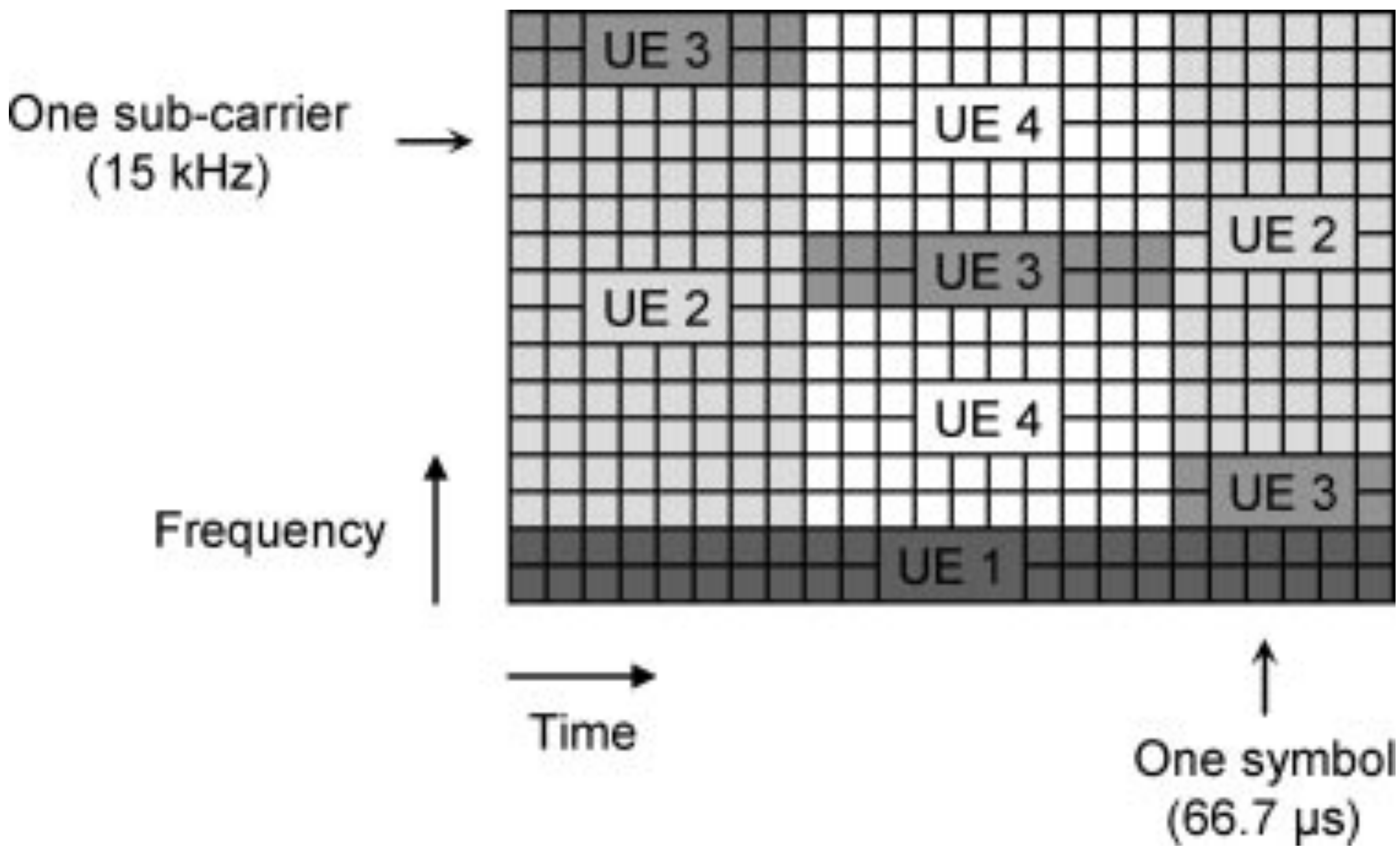


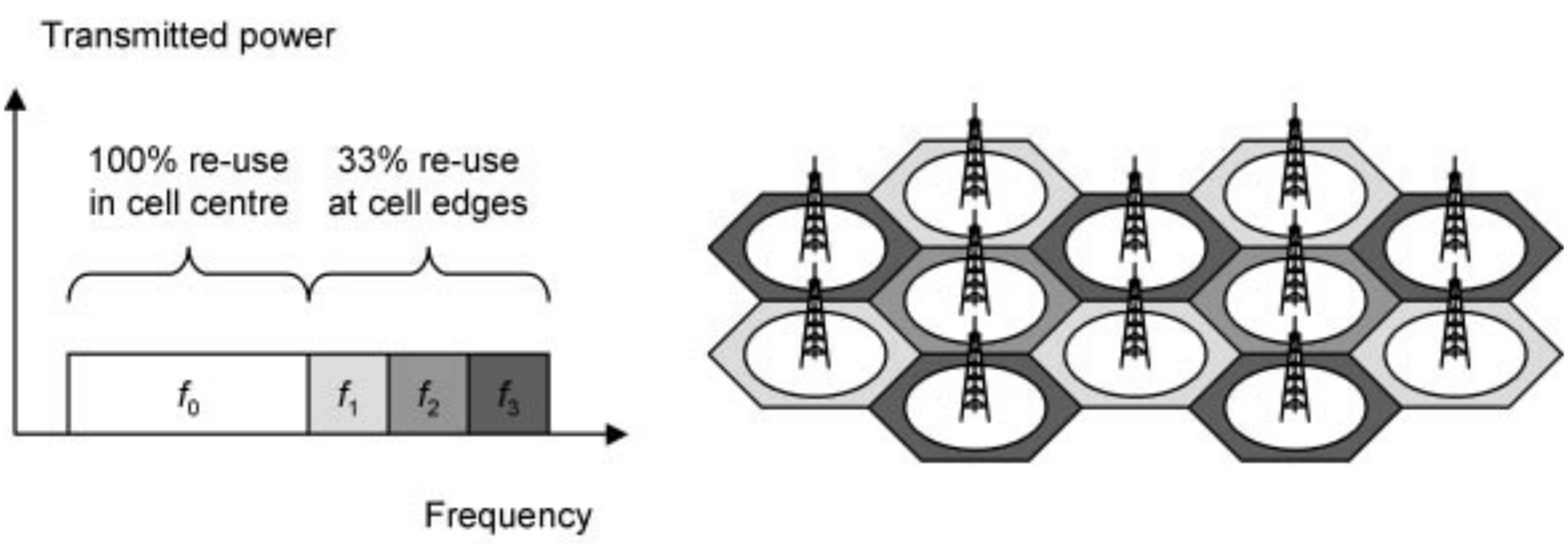
Figure 4.5 Implementation of time and frequency division multiple access when using OFDMA.

2.2 Fractional Frequency Re-Use

- In a mobile communication system
  - ✓ One BS can send information to a large number of mobiles
  - ✓ Every mobile has to receive a signal from one BS in the presence of interference from the others
- Need to minimize the interference, so that mobile can receive information successfully

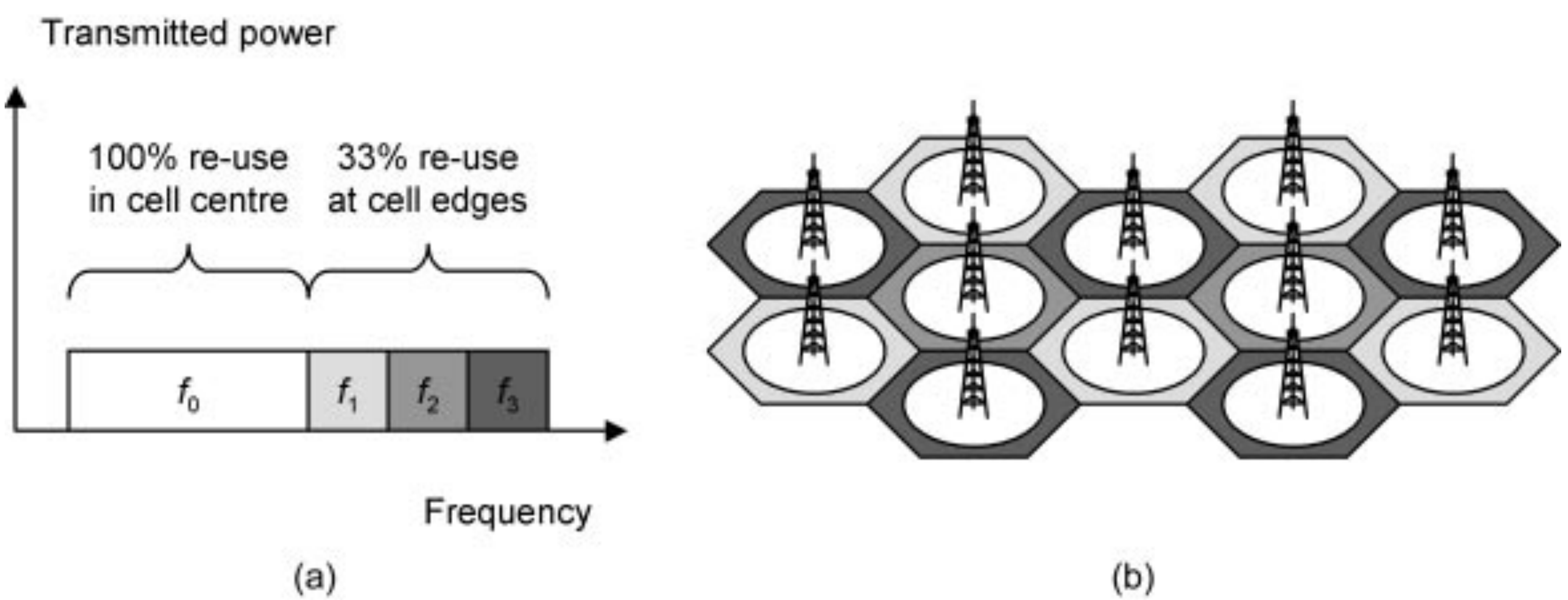
- Previous systems have used two different techniques
  - ✓ GSM
    - Nearby cells transmit using <u>different carrier frequencies</u>
    - Typically, <u>each cell</u> might use a <u>quarter</u> of the total bandwidth, with a re-use factor of 25%
    - This technique <u>reduces the interference</u> between <u>nearby cells</u>, but it means that the <u>frequency band</u> is used <u>inefficiently</u>
  - ✓ UMTS
    - Each cell has the same carrier frequency, with a re-use factor of 100%
    - This technique uses the frequency band more efficiently than before, at the expense of <u>increasing the interference</u> in the system

- LTE
  - ✓ Every BS can transmit in the <u>same frequency band</u>
  - ✓ It can <u>allocate the sub-carriers within that band</u> in a <u>flexible</u> way using <u>fractional frequency re-use</u>



(a) (b)

- Figure 4.6
  - ✓ Every BS is controlling one cell and every cell is sharing the same frequency band
  - ✓ Within that band, each cell transmits to nearby mobiles using the same set of sub-carriers, denoted f_0
  - ✓ The mobiles are close to their respective BSs, so the received signals are strong enough to overwhelm any interference
  - ✓ Distant mobiles receive much weaker signals, which are easily damaged by interference
    - To avoid this, neighboring cells can transmit to those mobiles using different sets of sub-carriers
    - Half the frequency band is reserved for nearby mobiles, while the remainder is divided into three sets, denoted f_1, f_2 and f_3, for use by distant mobiles
    - Resulting re-use factor: 67%



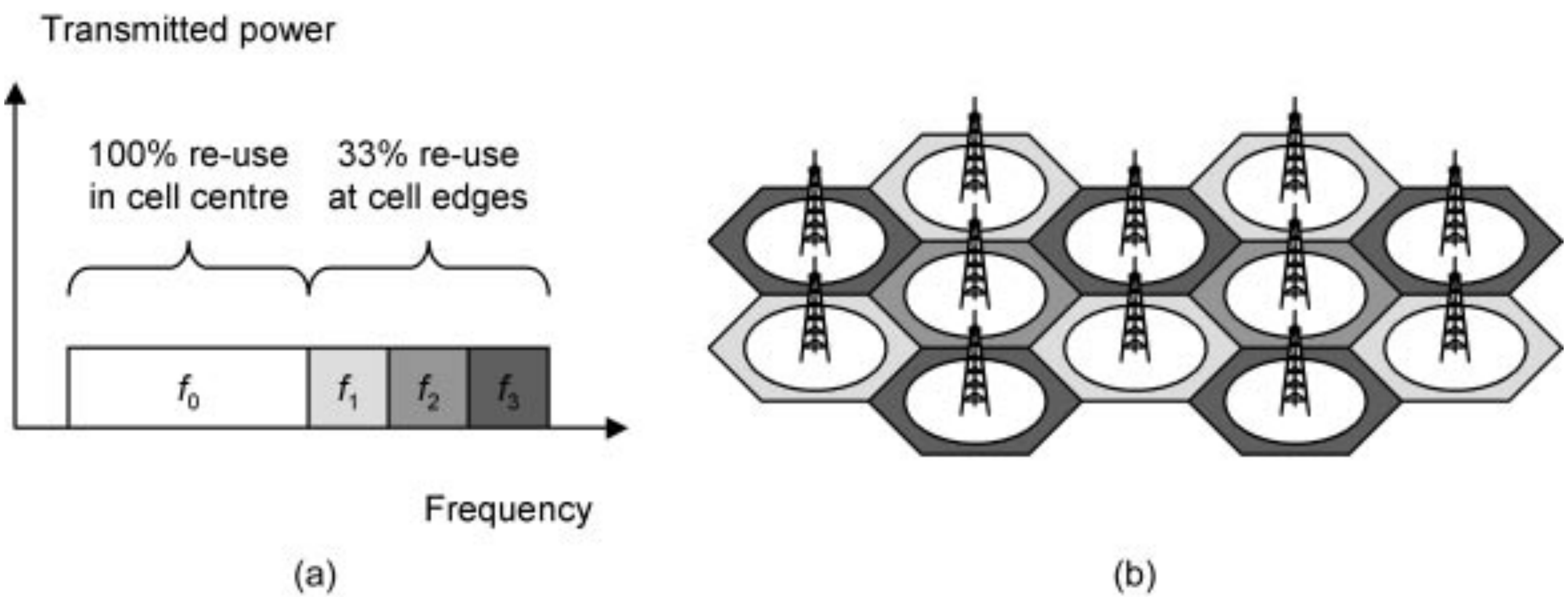
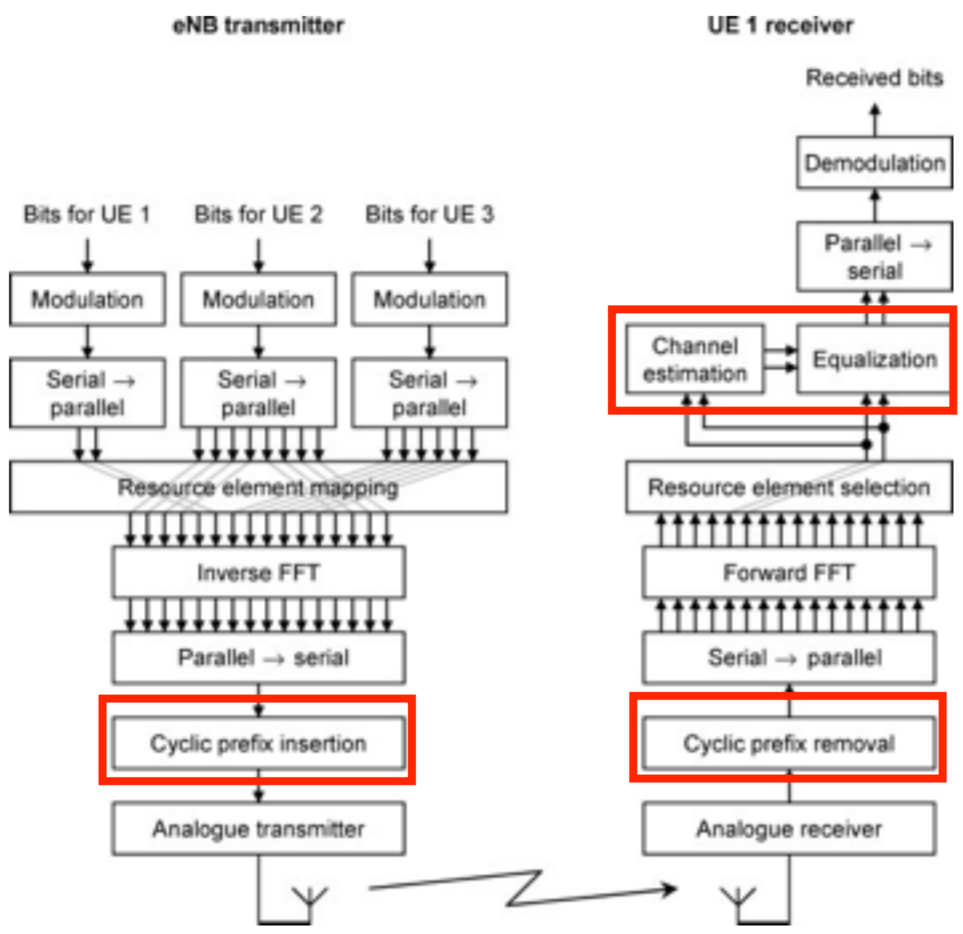


Figure 4.6 Example implementation of fractional frequency re-use when using OFDMA. (a) Use of the frequency domain. (b) Resulting network plan.

2.3 Channel Estimation

- Figure 4.7
  - ✓ A detailed block diagram of OFDMA
  - ✓ Two extra processes
    - The receiver contains the extra steps of channel estimation and equalization
    - The transmitter inserts a cyclic prefix into the data stream, which is then removed in the receiver



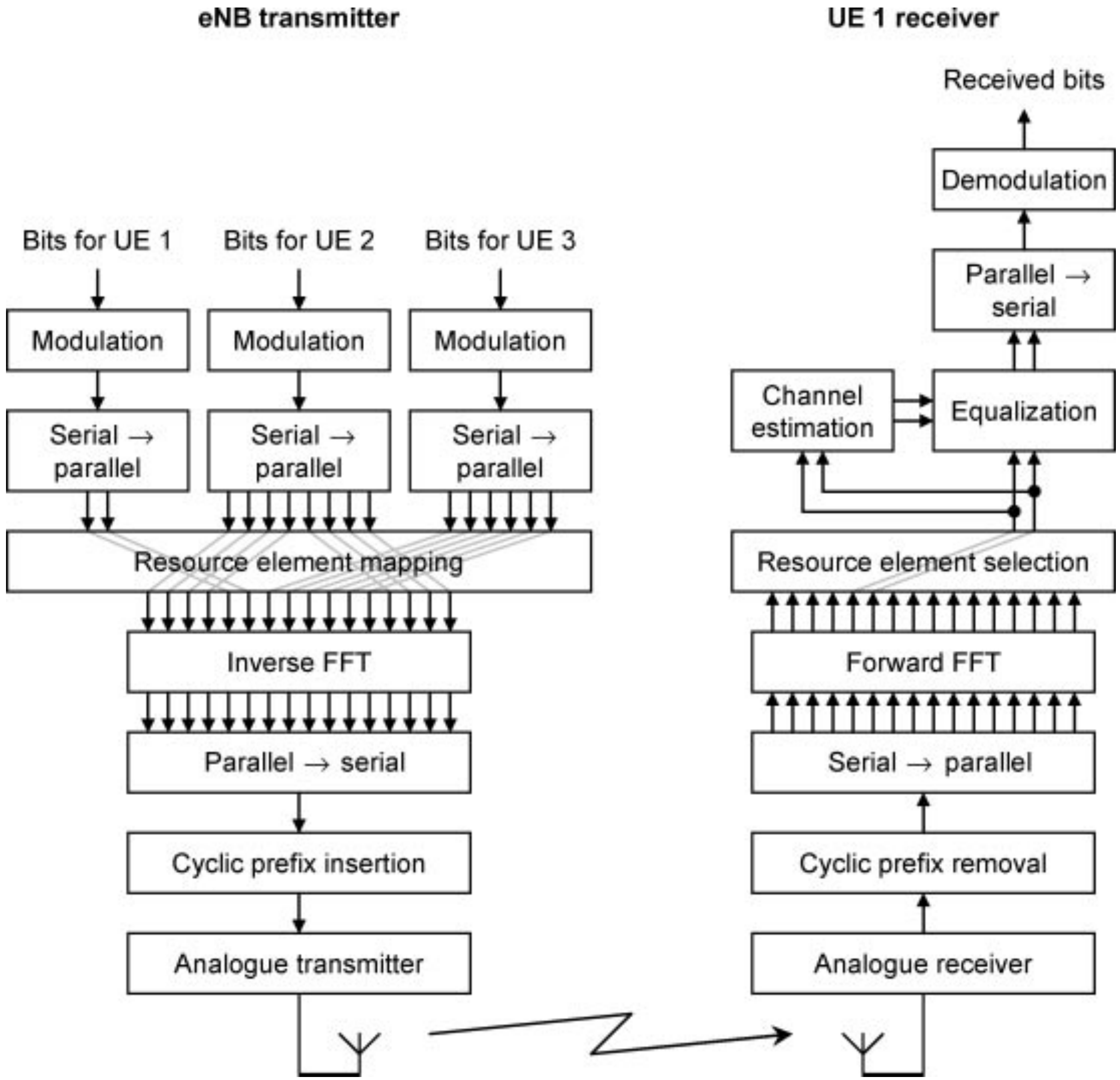
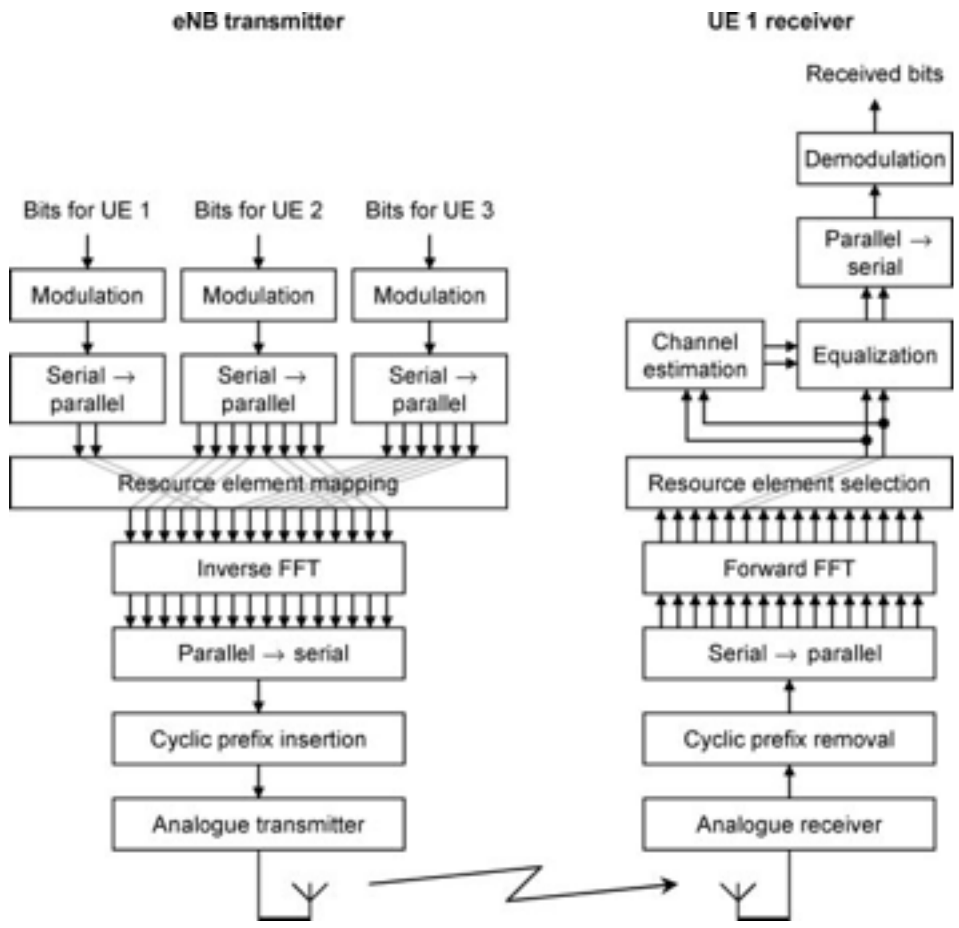


Figure 4.7 Complete block diagram of an OFDMA transmitter and receiver.

- Channel estimation
  - ✓ Each sub-carrier can reach the receiver with a completely arbitrary amplitude and phase
  - ✓ The OFDMA transmitter
    - Injects reference symbols into the transmitted data stream
  - ✓ The receiver
    - Measures the incoming reference symbols
    - Compares them with the ones transmitted
    - Uses the result to remove the amplitude changes and phase shifts from the incoming signal

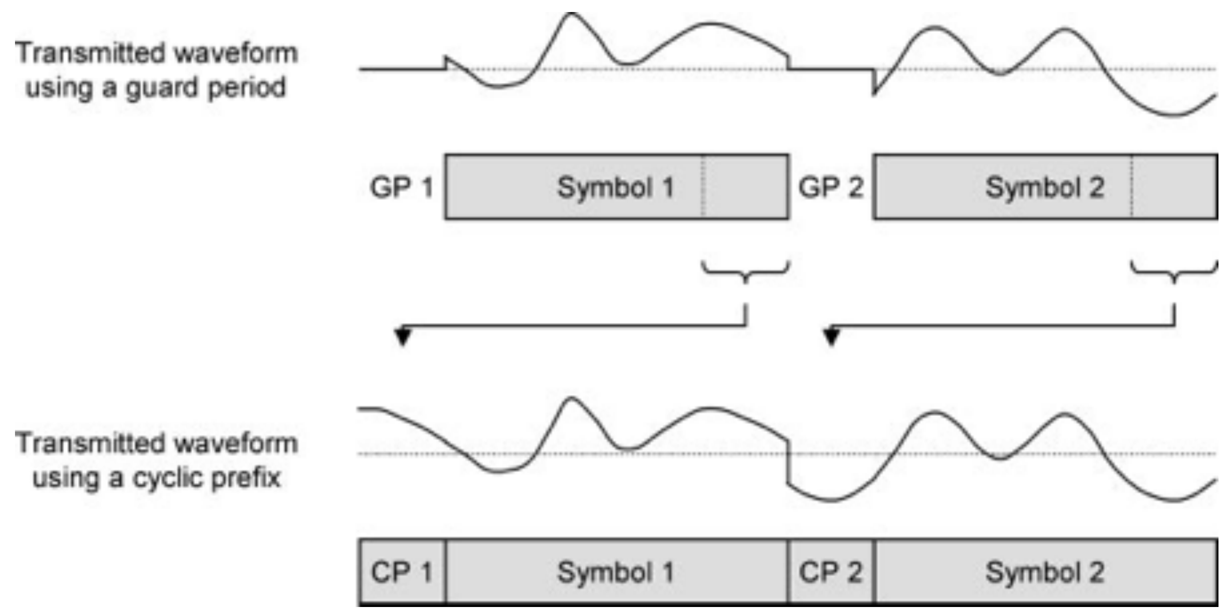


- In the presence of frequency-dependent fading
  - ✓ The amplitude changes and phase shifts are functions of frequency as well as time and
  - ✓ Affect the different sub-carriers in different ways
- To ensure that the receiver can measure all the information it requires
  - ✓ The LTE reference symbols are scattered across the time and frequency domains
- The reference symbols take up about 10% of the transmitted data stream, so do not cause a significant overhead

2.4 Cyclic Prefix Insertion

- A technique used to get rid of <u>inter symbol interference</u> (ISI)
- The basic idea is to insert a <u>guard period</u> (GP) before each symbol, in which <u>nothing</u> is transmitted
- If the guard period is <u>longer</u> than the <u>delay spread</u>, then the receiver can be confident of reading information from just <u>one symbol</u> at a time, without any overlap with the symbols that precede or follow
- The symbol reaches the receiver at <u>different times</u> on <u>different rays</u> and some <u>extra processing</u> is required to tidy up the confusion

- LTE uses a cyclic prefix (CP) insertion
  - ✓ The transmitter
    - Starts by inserting a guard period before each symbol, as before
    - It then copies data from the end of the symbol following, so as to fill up the guard period
  - ✓ The receiver
    - If the cyclic prefix is longer than the delay spread, then the receiver can still be confident of reading information from just one symbol at a time



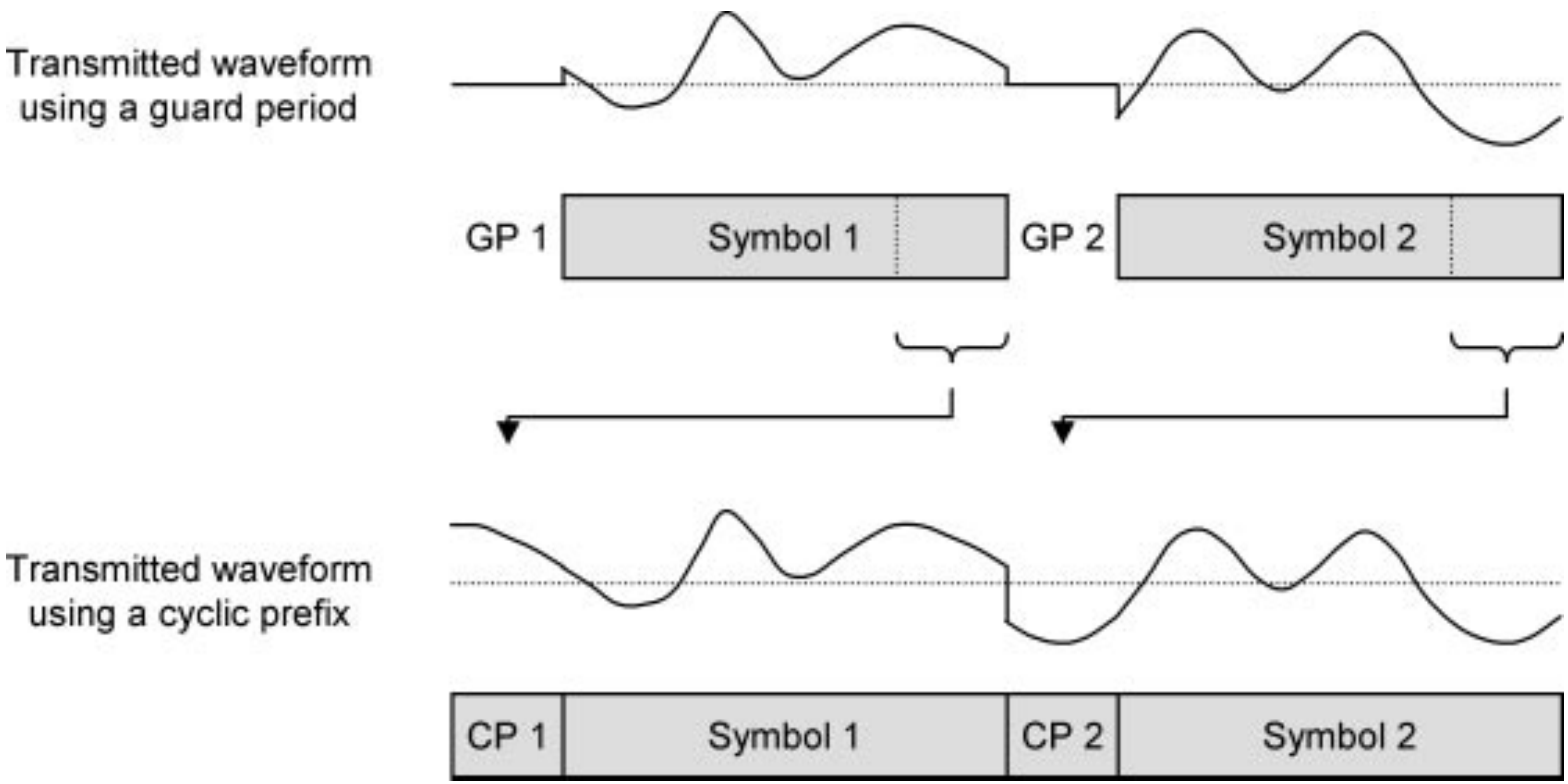
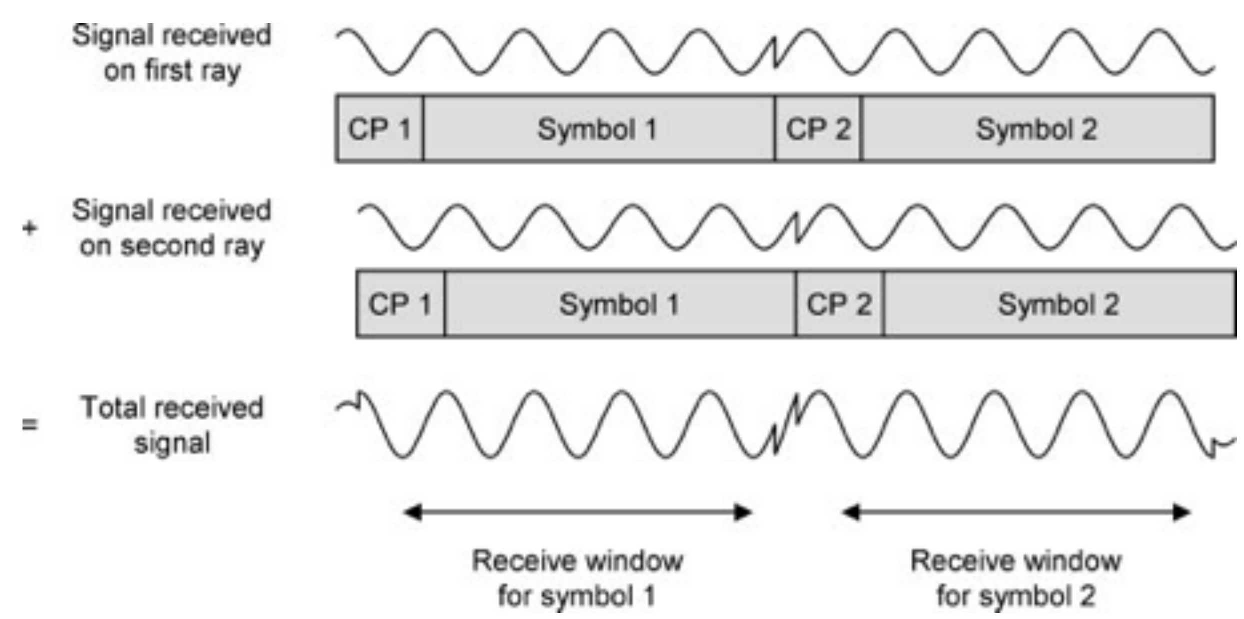


Figure 4.8 Operation of cyclic prefix insertion.

- Figure 4.9 shows how cyclic prefix insertion works
  - ✓ The transmitter
    - The transmitted signal is a sine wave, whose amplitude and phase change from one symbol to the next
    - As noted earlier, each symbol contains an exact number of cycles of the sine wave, so the amplitude and phase at the start of each symbol equal the amplitude and phase at the end
    - Because of this, the transmitted signal changes smoothly as we move from each cyclic prefix to the symbol following



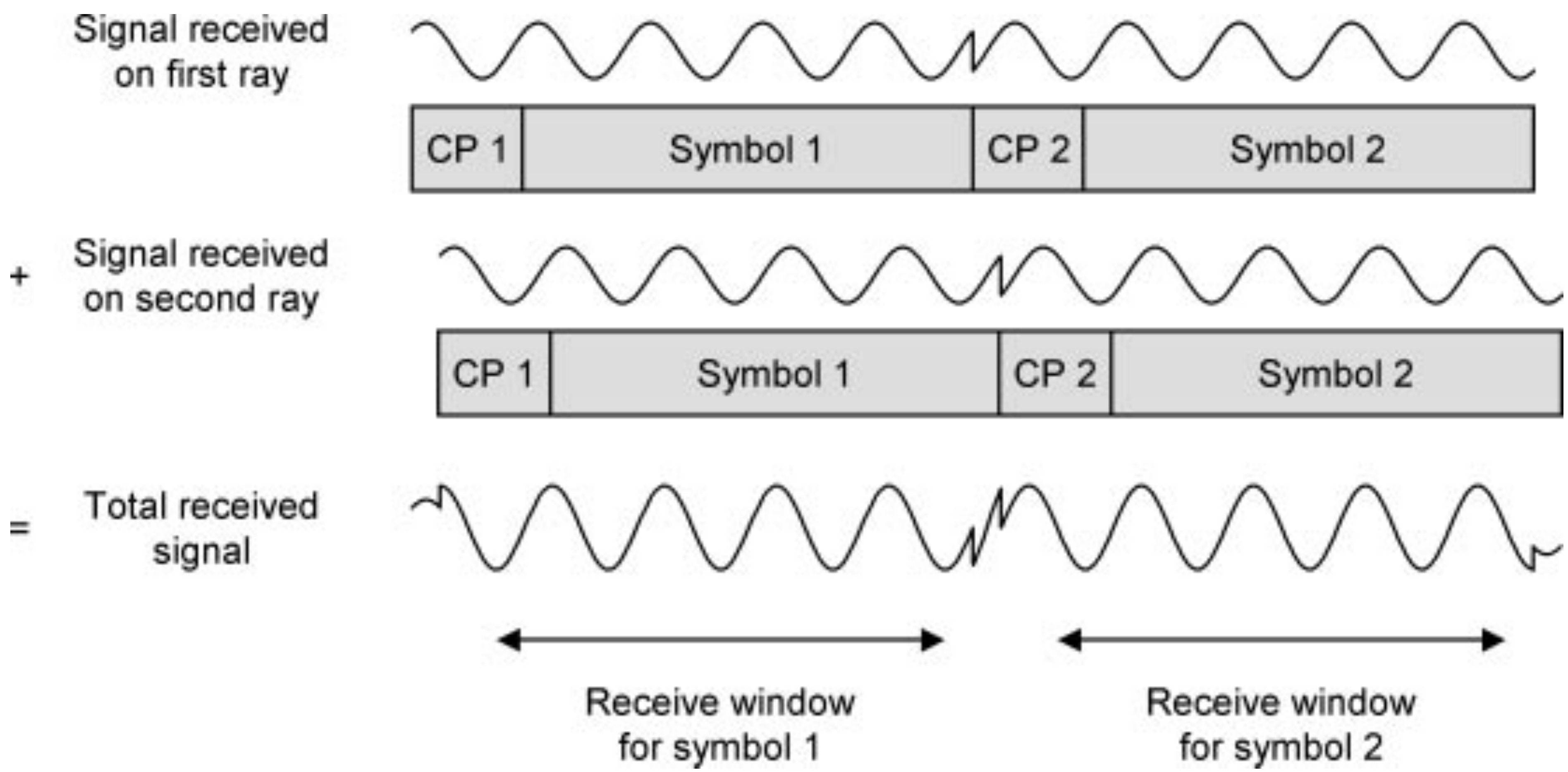


Figure 4.9 Operation of the cyclic prefix on a single sub-carrier.

- The receiver
  - In a <u>multipath</u> environment, the <u>receiver</u> picks up multiple copies of the transmitted signal with <u>multiple arrival times</u>
  - These <u>add</u> together at the receive antenna, giving a <u>sine wave</u> with the <u>same frequency</u> but a <u>different amplitude</u> and <u>phase</u>
  - The <u>received signal</u> still <u>changes smoothly</u> at the transition from a cyclic prefix to the symbol that follows
  - There are a few <u>glitches</u>, but these are only at the start of the cyclic prefix and the end of the symbol, where the preceding and following symbols start to interfere

- The receiver processes the received signal within a window whose length equals the symbol duration, and discards the remainder
- If the window is correctly placed, then the received signal is exactly what was transmitted, without any glitches, and subject only to an amplitude change and a phase shift
- But the receiver can compensate for these using the channel estimation and equalization techniques described above
- Admittedly the system uses multiple sub-carriers, not just one
- The sub-carriers do not interfere with each other and can be treated independently, so the existence of multiple sub-carriers does not affect this argument at all

- LTE uses a cyclic prefix of about 4.7 μs
  - ✓ This corresponds to a maximum path difference of about 1.4 km between the lengths of the longest and shortest rays, which is enough for all but the very largest and most cluttered cells
  - ✓ The cyclic prefix reduces the data rate by about 7%, but this is a small price to pay for the removal of ISI

2.5 Use of the Frequency Domain

- Let us now look in more detail at the way in which a mobile communication system uses the frequency domain
- In traditional analogue FDMA, a mobile has to measure the signal on one sub-carrier in the presence of interference from all the others
- To minimize the amount of interference, the sub-carriers have to be separated by wide guard bands
- The need for these guard bands implies that the system uses the frequency domain in an inefficient way

- Now consider the situation with OFDMA
- In the time domain, each sub-carrier starts life as a sine wave, but the modulation process makes its amplitude and phase change at intervals of the symbol duration T, which equals 66.7 μs
- This broadens the signal in the frequency domain, to a bandwidth of about T −1
- Figure 4.10 shows the details
- In the frequency domain, the amplitude of each sub-carrier oscillates either side of zero and crosses through zero at regular intervals of T−1. (Mathematicians will recognize this response as a sinc function (x−1 sin x).)

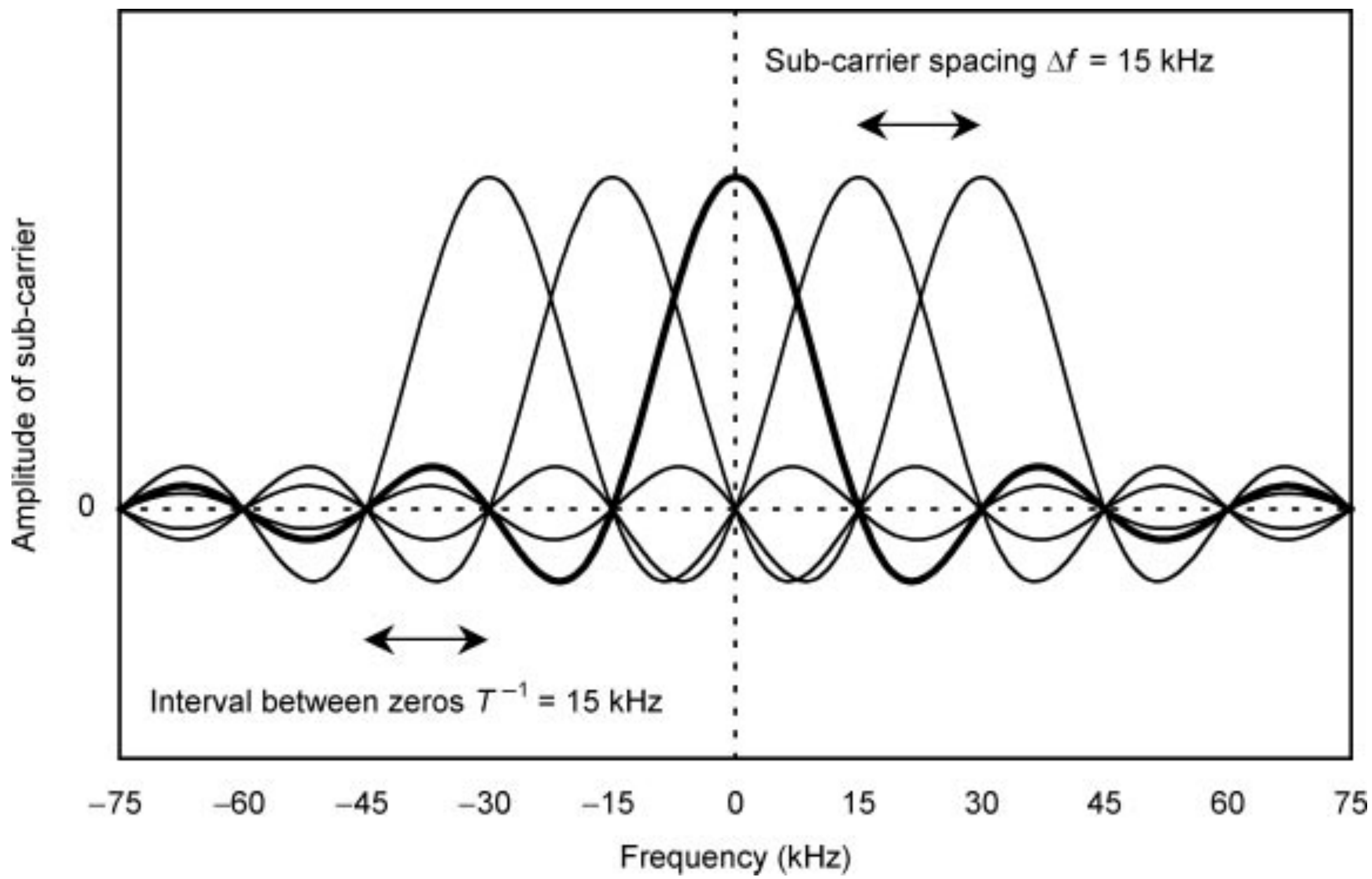


Figure 4.10 Amplitudes of the signals transmitted on neighboring sub-carriers, as a function of frequency.

- Now, the interval between adjacent sub-carriers is the sub-carrier spacing f
- If f = T −1, then the sub-carriers overlap in the frequency domain, but the peak response of one sub-carrier coincides with zeros of all the others
- As a result, the mobile can sample one sub-carrier and can measure its amplitude and phase without any interference from the others, despite the fact that they are closely packed together
- Sub-carriers with this property are said to be orthogonal

- This property means that OFDMA uses the frequency domain in a very efficient way and is one of the reasons why the spectral efficiency of LTE is so much greater than that of previous mobile telecommunication systems
- It also justifies the decision made in Section 4.1.2, when we set the symbol duration T equal to the reciprocal of the sub-carrier spacing f

2.6 Choice of Sub-Carrier Spacing

- The argument in the previous section works fine if the mobile is stationary
- If the mobile is moving, then any incoming rays are Doppler shifted to higher or lower frequencies
- The same applies to each of the OFDMA sub-carriers

- In a multipath environment, a mobile can be moving towards some rays, which are shifted to higher frequencies, but away from others, whose frequencies move lower
- As a result, the sub-carriers are not simply shifted: instead, they are blurred across a range of frequencies
- If a mobile tries to measure the peak response of one sub-carrier, then it will now receive interference from all the others
- We have therefore lost the orthogonality property from the previous section

- The amount of interference will still be acceptable, however, if the Doppler shift is much less than the sub-carrier spacing
- We therefore need to choose the sub-carrier spacing f as follows: f fD (4.1)
- where fD is the Doppler shift from Equation (3.4)
- LTE is designed to operate with a maximum mobile speed of 350 km hr−1 and a maximum carrier frequency of about 3.5 GHz, which gives a maximum Doppler shift of about 1.1 kHz
- This is 7% of the sub-carrier spacing, so it satisfies the constraint above

- There is another constraint on the parameters used by LTE
- To minimize the impact of inter-symbol interference, we need to choose the symbol duration T as follows:
- T τ (4.2)
- where τ is the delay spread from Equation (3.6)
- As we noted earlier, LTE normally works with a maximum delay spread of about 4.7 μs
- This is 7% of the 66.7 μs symbol duration, so it satisfies this second constraint

- We can draw the following conclusions
- If the sub-carrier spacing were much less than 15 kHz, then the system would be prone to interference between the sub-carriers at high mobile speeds
- If it were much greater, then the system would be prone to inter symbol interference in large, cluttered cells
- The chosen sub-carrier spacing is the result of a trade-off between these two extremes

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3. Single Carrier Frequency Division Multiple Access

- 3.1 Power Variations from OFDMA
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3.1 Power Variations from OFDMA

- OFDMA works well on the LTE downlink. However, it has one disadvantage: the power of the transmitted signal is subject to rather large variations
- To illustrate this, Figure 4.11(a) shows a set of sub-carriers that have been modulated using QPSK, and which therefore have constant power
- The amplitude of the resulting signal (Figure 4.11b) varies widely, with maxima where the peaks of the sub-carriers coincide and zeros where they cancel
- In turn, these variations are reflected in the power of the transmitted signal (Figure 4.11c)

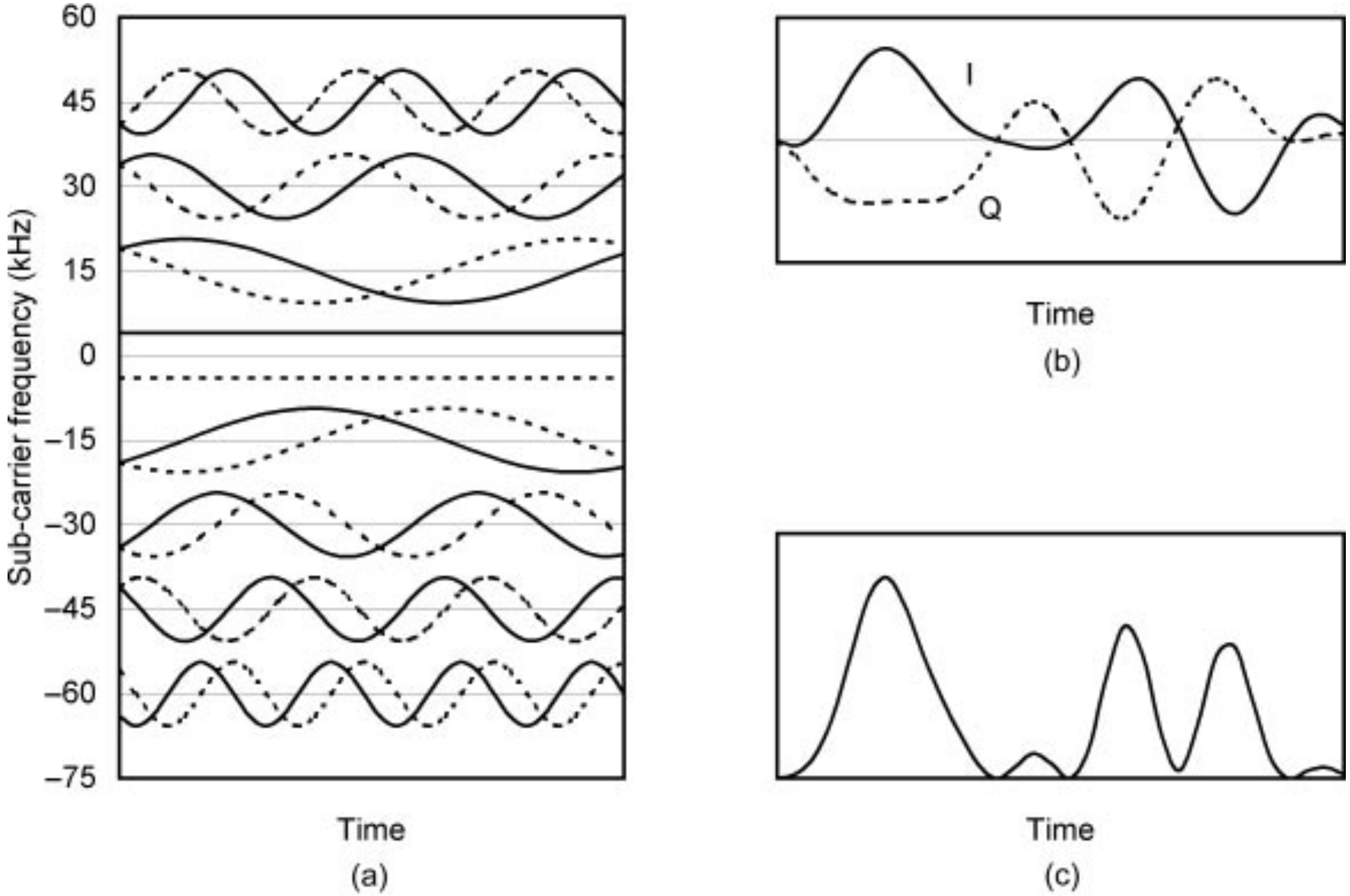

Figure 4.11 Example OFDMA waveform.
(a) Amplitudes of the individual sub-carriers.
(b) Amplitude of the resulting OFDMA waveform.
(c) Power of the OFDMA waveform.

- These power variations can cause problems for the transmitter's power amplifier
- If the amplifier is linear, then the output power is proportional to the input, so the output waveform is exactly the shape that we require
- If the amplifier is non-linear, then the output power is no longer proportional to the input, so the output waveform is distorted

- Any distortion of the time-domain waveform will distort the frequency-domain power spectrum as well, so the signal will leak into adjacent frequency bands and will cause interference to other receivers

- In the downlink, the base station transmitters are large, expensive devices, so they can avoid the problem by using expensive power amplifiers that are very close to linear
- In the uplink, a mobile transmitter has to be cheap, so does not have this option
- This makes OFDMA unsuitable for the LTE uplink

3.2 Block Diagram of SC-FDMA

- The power variations described above arise because there is a one-to-one mapping between symbols and sub-carriers
- If we mixed the symbols together before placing them on the sub-carriers, then we might be able to adjust the transmitted signal and reduce its power variations
- For example, when transmitting two symbols x1 and x2 on two sub-carriers, we might send their sum x1 + x2 on one sub-carrier, and their difference x1 – x2 on the other
- We can use any mixing operation at all, as the receiver can reverse it: we just need to find one that minimizes the power variations in the transmitted signal

- It turns out that a suitable mixing operation is another FFT, this time a forward FFT
- By including this operation, we arrive at a technique known as single carrier frequency division multiple access (SC-FDMA), which is illustrated in Figure 4.12

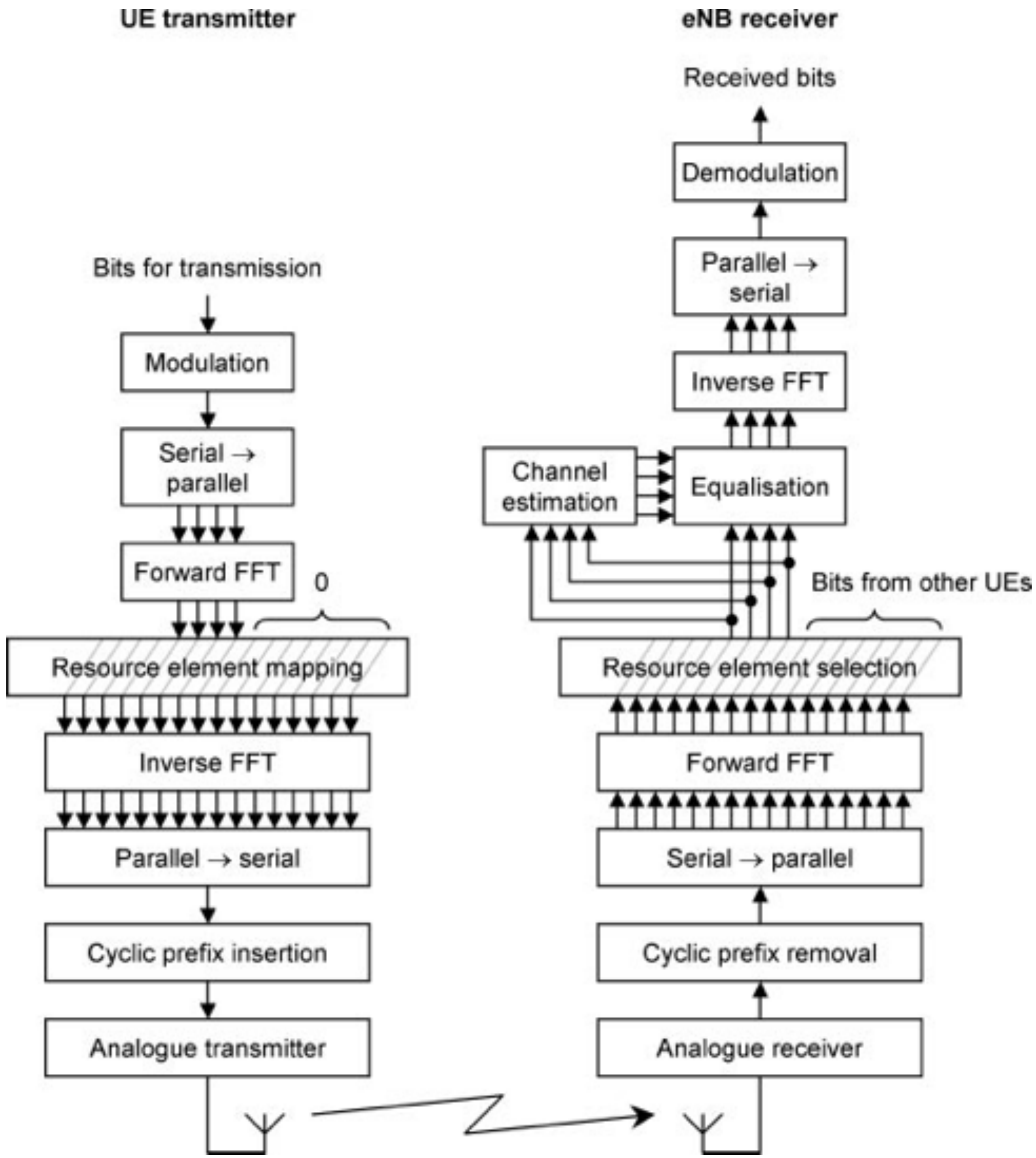

Figure 4.12 Block diagram of an SC-FDMA transmitter and receiver.

- In this diagram, there are three differences from OFDMA
- The main difference is that the SC-FDMA transmitter includes an extra forward FFT, between the steps of serial-to-parallel conversion and resource element mapping
- This mixes the symbols together in the manner required to minimize the power variations and is reversed by an inverse FFT in the receiver

- The second difference arises because the technique is used on the uplink
- Because of this, the mobile transmitter only uses some of the sub-carriers: the others are set to zero, and are available for the other mobiles in the cell
- Finally, each mobile transmits using a single, contiguous block of sub-carriers, without any internal gaps
- This is implied by the name SC-FDMA and is necessary to keep the power variations to the lowest possible level

- We can understand how SC-FDMA works by looking at three key transmission steps: the forward FFT, the resource element mapper and the inverse FFT
- The input to the forward FFT is a sequence of symbols in the time domain
- The forward FFT converts these symbols to the frequency domain, the resource element mapper shifts them to the desired centre frequency and the inverse FFT converts them back to the time domain
- Looking at these steps as a whole, we can see that the transmitted signal should be much the same as the original modulated waveform, except for a shift to another centre frequency
- But the power of a QPSK signal is constant (at least in the absence of additional filtering), and it hardly varies at all in the cases of 16-QAM and 64-QAM
- We have therefore achieved the result we require, of transmitting a signal with a roughly constant power

- Figure 4.13 shows the resulting waveforms, from an example in which the mobile is using four sub-carriers from a total of 256
- The input (Figure 4.13a) is a sequence of four QPSK symbols, with [I, Q] values of [1, 1], [1, −1], [−1, 1] and [−1, −1]
- If the data are transmitted on the central four sub-carriers, then the result (Figure 4.13b) looks very like the original QPSK waveform
- The only difference is a smooth interpolation between the 256 samples in the time domain, which wraps round the ends of the data sequence due to the cyclic nature of the FFT
- If we instead shift the data by 32 sub-carriers, then the only change (Figure 4.13c) is the introduction of some extra phase rotation into the resulting waveform

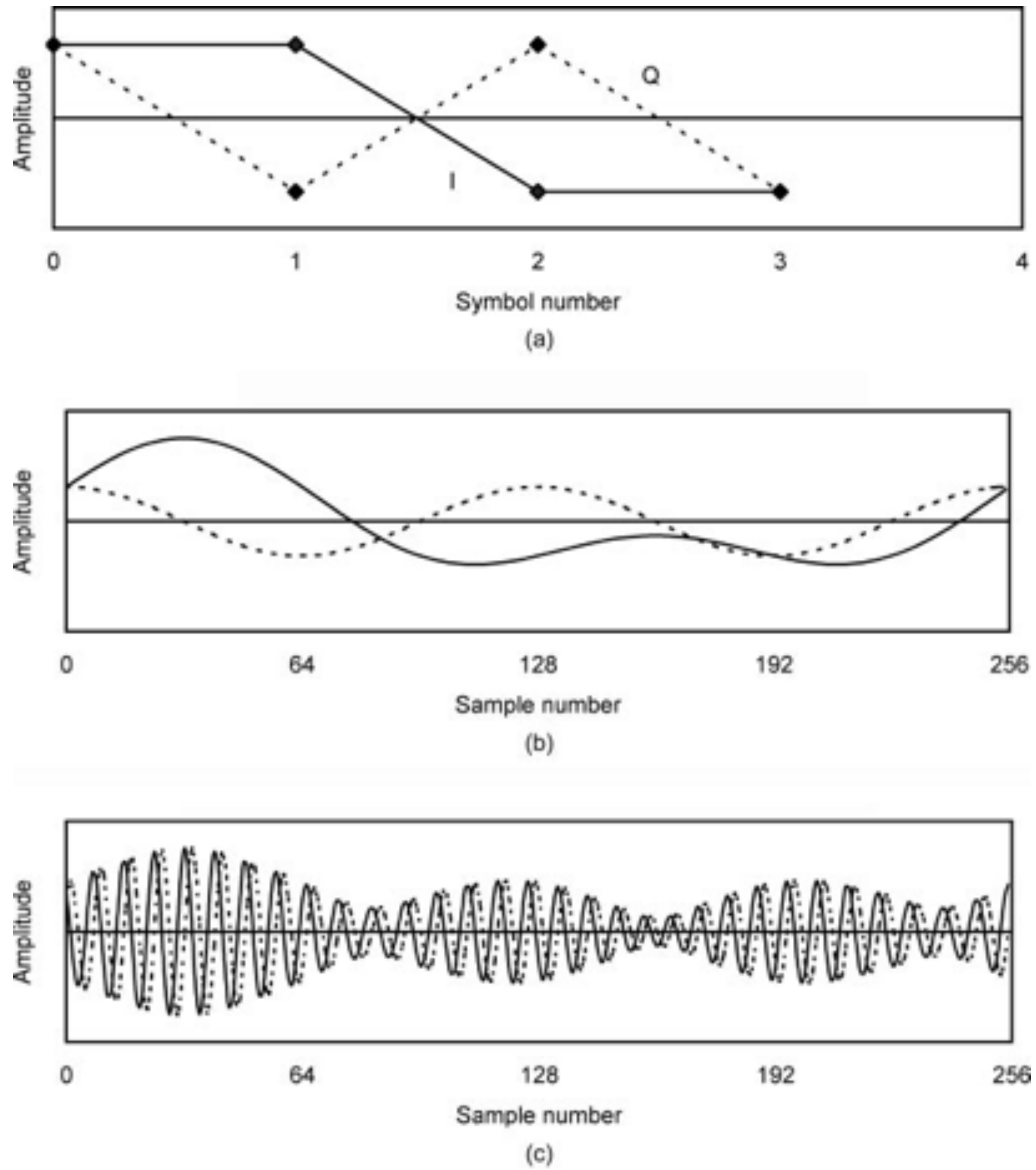

Figure 4.13 Example SC-FDMA waveform. (a) Transmitted symbols. (b) Resulting SC-FDMA waveform, if the data are transmitted on the central 4 sub-carriers out of 256. (c) SC-FDMA waveform, if the data are shifted by 32 sub-carriers.

- We don’t use SC-FDMA in the downlink, because the base station has to transmit to several mobiles, not just one
- We could add one forward FFT per mobile to Figure 4.7, but that would destroy the single carrier nature of the transmission, and would allow the high power variations to return
- Alternatively, we could add a single forward FFT across the whole of the downlink band
- Unfortunately that would spread every mobile’s data across the whole of the frequency domain, and would remove our ability to carry out frequency-dependent scheduling
- Either way, SC-FDMA is unsuitable for the LTE downlink