行政院國家科學委員會補助專題研究計畫成果報告

程式化 OFDM 接收器架構
Programmable OFDM Receiver Architecture

計畫類別： ο**個別型計畫**　　□**整合型計畫**
計畫編號：NSC 89－2213－E－002－120
執行期間： 89 **年** 8 **月** 1 **日 至** 90 **年** 7 **月** 31 **日**

計畫主持人：陳光禎教授

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執行單位：國立台灣大學電信工程研究所

中華民國 90 **年** 7 **月** 31 **日**

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一、中文摘要

殘餘符際干擾與過大的極均功率比是兩個正交分頻多工系統中為人熟知的問題。我們提出一種名為『多載波平行決策回授解碼』的方法以消除殘餘符際干擾，這個方法基於『簡化狀態序列估測』的概念，可在正交分頻多工系統中結合柵欄碼調變與決策回授等化。其傑出效能可藉由數個基於不同的子載波數目、通道環境、柵欄碼調變方式的模擬結果得到證明。另外，我們也定義了影響極均功率比的相關參數並且推導了不同柵欄碼調變方式之極均功率比的適當上下限來研究如何縮減極均功率比。再者，為了探索正交分頻多工系統的可行性並且應用軟體無線電的概念，我們設計並且實作兩個以德儀TMS320C6201 **數位訊號處理器的發展電路板為基礎的收發器來建構一個整合的具有軟體無線電架構的適調速率正交分頻多工通訊系統。這個可程式化的架構可為將來更先進的正交分頻多工系統的發展提供一個彈性化的實作平台。**

關鍵詞：正交分頻多工，殘餘符際干擾，極均功率比，柵欄碼調變，多維度柵欄碼調變，決策回授等化，多路徑衰退，適調速率，編碼，同步，等化，TMS320C62，TLC5540，THS3001，TLC7524，THS4001

Abstract:

Residual intersymbol interference (ISI) and large peak-to-average (PAP) power ratio are two well-known problems in orthogonal frequency division multiplexing (OFDM) systems. We propose an approach named “multi-carrier parallel decision feedback decoder” (MC-PDFD) based on the concept of “reduced state sequence estimation” (RSSE) to combine trellis-code modulation (TCM) and decision feedback equalization (DFE) in OFDM systems. The excellent performance of MC-PDFD to remove residual ISI is convinced by several simulation results with different number of subcarriers, channel conditions, and trellis-coded modulation techniques. In addition, the related parameters that affect the value of PAP ratio are defined and the proper upper and lower bounds for different trellis-coded modulation schemes are derived to investigate the reduction of PAP. Furthermore, to explore the feasibility of OFDM systems and the concept of software radio, we design and implement two transceivers based on the EVM board with TI’s TMS320C6201 DSP to constitute an integrated rate-adaptive OFDM communication system with software radio architecture. This programmable architecture shall provide a flexible implementation platform for future developments of advanced OFDM systems.

Keywords: OFDM, residual ISI, PAP, TCM, multi-dimensional TCM, DFE, multipath fading, rate-adaptive, coding, synchronization, equalization, TMS320C62, TLC5540, THS3001, TLC7524, THS4001

二、緣由與目的

The rapid growth of communication for video, voice, data, and the equally rapid pervasion of mobile telephony justify the great expectation for mobile multimedia. These multimedia services require the transmission of very high data rate over broadband radio channels. In the case of wired networks, high bit-rate services are principally not a technical problem due to the channel behavior. But for radio transmission, high data rate lead to additional technical considerations. A broadband radio channel is characterized both by time variant behavior due to a moving receiver or transmitter, and by frequency-selective fading caused by multipath propagation. For conventional single carrier systems, channel equalization can be very complicated. Therefore, a proper modulation technique supporting high data rate with sufficient robustness to radio channel impairments is necessary. Orthogonal frequency division multiplexing (OFDM) [4][5], adopted by ETSI HIPERLAN/2 and IEEE 802.11a wireless LAN standards, is a leading-edge multicarrier technique in high-speed wireless data communications and a strong candidate for 4G as well. One of the most important reasons to adopt OFDM is its robustness against frequency selective fading. This technique turns the original channel into several narrowband flat fading subchannels thus simplifies the equalizer structure.

However, there are still problems that have to be dealt with. One is the problem of residual ISI, which is caused by the multipath effects with channel memory longer than guard interval. In such critical environment, the inherent advantage of OFDM to combat multipath distortion is not enough. Additional method should be included to solve the problem of residual ISI.

Another problem in OFDM systems is the large peak-to-average power (PAP) ratio [6][7]. This drawback causes nonlinear distortion from hardware devices since large peak power makes those amplifiers and AD/DA converters to operate in the saturation region, and thus no more linear operation can be predicted. Therefore, it is essential to reduce peak-to-average power (PAP) ratio in an OFDM system so that all devices can function in the linear region.

To solve the residual ISI problem, special consideration shall be taken in the design of the equalization and coding schemes. Trellis-coded modulation (TCM) [1] with its near optimal performance and relatively less complicated implementation strikes the best compromise between performance and complexity, hence is a good choice for our coding scheme. Conventionally, receivers employing TCM under ISI environment use linear equalizers and soft-decision Viterbi decoders to do the tasks of equalization and decoding separately. Unfortunately, linear equalization suffers from noise enhancement and is better substituted with DFE. However, DFE cannot be combined directly with Viterbi decoding because it requires reliable, delay-free feedback decisions, which is available after several signaling intervals.

To remedy this problem, a method named “reduced state sequence estimation” (RSSE) was proposed [2] and can be thought as a way that performs equalization and decoding simultaneously for single carrier communication systems. We apply the idea of RSSE to multicarrier communication systems to mitigate the effects of residual ISI and an approach named “multicarrier parallel decision feedback decoder” (MC-PDFD) is proposed. It utilizes the immediate decision feedback stored in each path history in the decoding trellis to remove the ISI effects in the received signal and thus avoids the same feedback information as in the conventional DFE.

Furthermore, to solve the PAP problem, we also combine OFDM with multi-dimensional trellis coded modulation scheme [3]. Due to the nature of parallel transmission, each dimension in multi-dimensional trellis coded modulation scheme is conveniently distributed to each subcarrier in the OFDM systems, and can be treated independently by dealing with the corresponding subcarrriers. Applying multi-dimensional TCM to OFDM systems not only benefits to reduce large PAP ratio but improves the system performance due to the additional degrees of freedom.

With the exponentially blowup of cellular mobile systems, it has produced, a plethora of analog and digital standards. Toward the definition of a unique standard for future mobile systems, software radio concept is emerging as a potential pragmatic solution to this problem. The term software radio stands for the functionalities of radio interface defined by software, which is usually implemented by dedicated hardware. The presence of software defining the radio interface necessarily implies the use of DSPs to replace the dedicated hardware, to execute, in real time, the necessary software. In a word, software radio is an emerging technique, thought to build flexible radio systems, multiservice, multistandard, multiband, reconfigurable and reprogrammable by software.

In order to explore the feasibility of OFDM systems and the concept of software radio, we design and implement two transceivers based on the EVM board with TI’s TMS320C6201 DSP [8] to constitute an integrated rate-adaptive OFDM communication system with software radio architecture. To the future integration of our MC-PDFD scheme in an OFDM system, we choose the modulation/coding scheme in our implementation as the principal functionality defined by software. In our system, three different modulation and coding schemes are designed to support multirate OFDM with the capability to adaptively adjust the transmission rate according to different channel conditions. This rate-adaptive feature not only enables our system to the optimum utilization of the channel capacity but also fit the need to support multirate services in future wireless/mobile multimedia communication systems.

三、結果與討論

As mentioned above, the idea of PDFD came from TCM-encoded, serial communication systems. In the serial case, it is straightforward that ISI can be removed if we subtract an additional term, e.g. the convolution of channel and transmitted symbols, when calculating the branch metric in the Viterbi decoding process. However, in the case of parallel transmission, especially in an OFDM system with FFT operation, directly adding the convolution result of channel and data into branch metric is useless because the effects of parallel modulation and subcarriers are not taken into account. Therefore, a modified branch metric of PDFD for OFDM systems to cancel the residual ISI is needed.

The system model of our system is shown in Figure 1. Please notice that the tasks of removing residual ISI and trellis decoding are performed at the same time. Based on this model, the branch metric of PDFD for OFDM system is obtained as

$$b(k;n) = \left| y(k,n) - x(k,n)H_k - \sum_{l=1}^{K-G} X(N-l,n-1)e^{-j\frac{2\pi k}{N}(K-l)} \sum_{m=1}^{K-l} h(K-m+1)e^{j\frac{2\pi km}{N}} \right|^2 \tag{1}$$

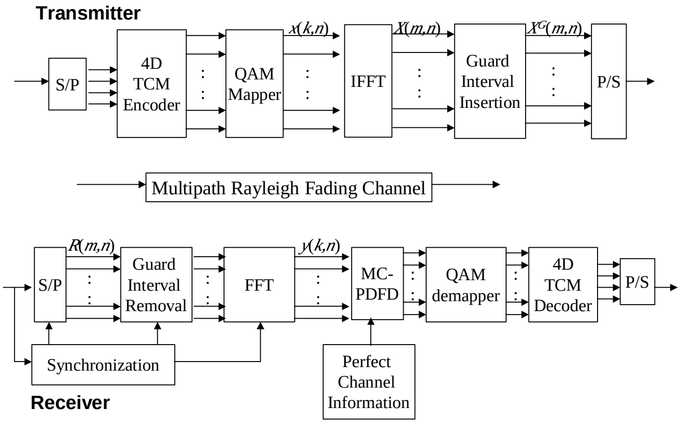

Figure 1. The block diagram of our OFDM system

From (1), we can observe that increasing the channel length and the number of subcarriers results in additional terms in $X(m,n-1)$ and residual ISI. Given the branch metric above, the decoding procedure of PDFD for OFDM systems is as follows.

1) Calculate $X(m,n-1)$.
2) Calculate the ISI term.
3) Select the closest point from parallel transitions.
4) Proceed with usual Viterbi algorithm.

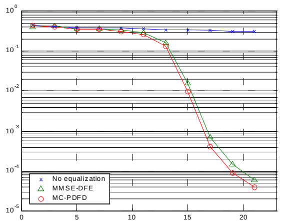

Figure 2. Performance of MC-PDFD with 2D-TCM OFDM

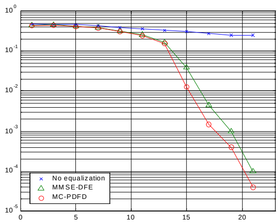

Figure 3. Performance of MC-PDFD with 4D-TCM OFDM

With this decoding procedure, we then illustrate the performance of PDFD for OFDM systems with different TCM encoding schemes (2D-TCM and 4D-TCM). In Figure 2 and Figure 3, OFDM systems with 4 subcarriers are simulated with guard interval G=1, path number K=2. The channel power gain is assumed to be exponential delay profile with power gain h_0 = 0.7856, h_1 = 0.1753, h_2 = 0.0391 and fixed delay equal to the reciprocal of the subcarrier spacing. As references, the performances of one-tap DFE using MMSE criterion are also plotted. From these figures, we can see that, with the same channel information, MC-PDFD outperforms the conventional decision feedback equalizer. The difference grows with larger signal-to-noise ratio (SNR).

Next, we shall illustrate the performance of MC-PDFD with larger channel length, i.e. the environment with residual ISI. We take the parameters in IEEE 802.11a and the channel condition is assumed to be Rayleigh multipath fading. The number of subcarriers N = 64, guard interval G = 16, the channel multipath K = 30, and the channel power gain is assumed to be exponential delay profile with fixed delay equal to the reciprocal of the subcarrier spacing. The results are shown in Figure 4 and Figure 5 with 2D-TCM and 4D-TCM respectively.

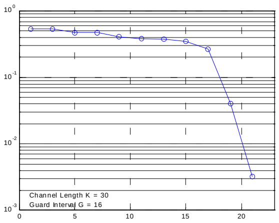

Figure 4. Performance of MC-PDFD with 2D-TCM OFDM with larger K

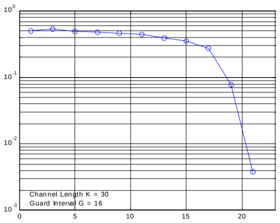

Figure 5. Performance of MC-PDFD with 4D-TCM OFDM with larger K

From all these simulation results, we can observe that the proposed method (MC-PDFD) effectively remove residual ISI, no matter in 2-dimensional TCM or multi-dimension TCM schemes, and its performance is as good as conventional DFE which is optimal in the sense of minimizing mean square error with perfect signal-to-noise ratio (SNR) information and takes only the job of equalization. For cases with small number of subcarriers, MC-PDFD even outperforms the DFE. Therefore, MC-PDFD offers an effective way to solve the problem of residual ISI in OFDM communication systems with an additional benefit that accomplishes the tasks of equalization and trellis decoding altogether at the same time.

In the above discussion, the assumption of perfect channel information is always held, however, there are usually estimation errors that block us from the ideal situation, and thus it is desirable to know the robustness of the designed MC-PDFD with practical channel estimator. Typically, estimation errors exist with standard deviation ranging from 0.1 to 0.4. Here the standard deviation is defined as

$$\text{Standard Deviation} \equiv \text{S} = \sqrt{\frac{\sum_{k=0}^{K} | \hat{H}_k - H_k |^2}{\sum_{k=0}^{K} | H_k |^2}} \qquad (2)$$

where $\hat{H}_k$ is the estimated channel value corresponding to the kth subcarrier in the frequency domain. Figure 6 and Figure 7 illustrate the performance of MC-PDFD with different S in several OFDM systems. As we can see from Figure 6 and Figure 7, the proposed MC-PDFD works normally with somewhat performance degradation when the standard deviation of the estimated channel does not exceed 0.3. When the deviation grows larger, MC-PDFD cannot sustain and starts malfunctioning. In this case, the resulting bit error rate stays high and does not go down with larger SNR due to the accumulated nature of Viterbi algorithm. For a Viterbi decoder, it is easy to distinguish the right path from the others if correct channel is used, since there would be a gap in the accumulated metric. But for erroneous channel values, this gap would finally disappear and thus stops the algorithm from correct path selection. Therefore, it is important to choose a proper channel estimator when applying MC-PDFD. On the other hand, MC-PDFD is less sensitive to non-perfect channel information, compared to DFE with Viterbi decoder. We can find that MC-PDFD performs equally or even better than DFE-Viterbi decoder under erroneous channel estimates. One possible reason is that MC-PDFD uses different decision feedbacks from the path history, unlike DFE, which feedbacks the same decision when decoding a symbol. Therefore, DFE-Viterbi decoder blurs the differences between paths faster than MC-PDFD, resulting in higher bit error rates.

In order to investigate the capability of PAP reduction of our MC-PDFD scheme combined with multidimensional TCM, the upper bound and lower bound of the PAP of OFDM systems with 2D-MC-PDFD and 4D-MC-PDFD are derived. The results are shown in Figure 8 and Figure 9 with fixed Q (number of bits transmitted per interval) and D (number of data carrier)

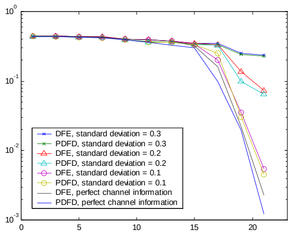

Figure 6. BER comparison of 2D-MC-PDFD and DFE-VA with imperfect channel information

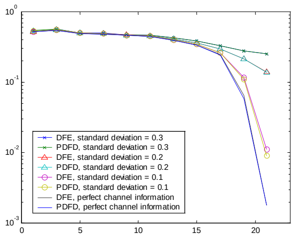

Figure 7. BER comparison of 4D-MC-PDFD and DFE-VA with imperfect channel information

respectively. We can see that parameters D, Q and N affect the bounds of the peak-to-average (PAP) ratio. In general, larger N and D result in higher values. Besides, different trellis coded modulation schemes also have influences on the PAP ratio. We can see that using multidimensional TCM helps to reduce peak power when the number of data carrier is small. It is because that in multidimensional TCM, the outer points are less probable to be selected than in 2D-TCM, a consequence of the way in constructing a multidimensional constellation. Furthermore, as Q increases, the peak power difference between 2D and 4D TCM also increases. This is an inherent advantage of multidimensional TCM since the size of its constellation grows much more slowly, unlike 2D TCM, in which constellation size doubles when Q increases by one. It is also worth reminding that there is no additional software or hardware needed to achieve lower PAP ratio by choosing multi-dimensional TCM. In consequence, multi-dimensional TCM is considered as a good candidate for coding scheme in OFDM systems.

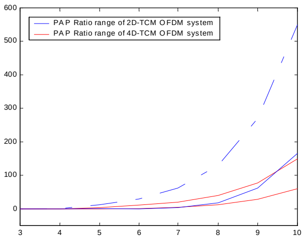

Figure 8. PAP comparison of TCM-OFDM with D=48

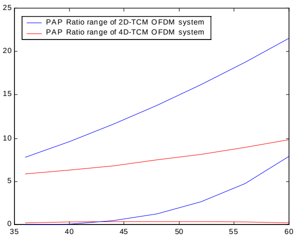

Figure 9. PAP comparison of TCM-OFDM with Q=5

Finally, we shall demonstrate how we design and implement the rate-adaptive OFDM transceivers with the TMS320C6201 DSP. The block diagram of our rate-adaptive OFDM system is shown in Figure 10. While our system focuses on the baseband processing, we use two EVM boards each with a TI's TMS320C6201 fixed-point DSP as baseband processor to provide reliable data transmission. As for the daughter-boards used for mixed-signal processing, we make use of TLC5540, TLC7524, THS3001, and THS4001 [9] for ADC, DAC, input buffer, and output buffer respectively. We also include complete baseband to RF implementation in 2.45GHz unlicensed ISM band using the RFMD radio module [10] to demonstrate the practicability. Our sophisticated design of the inner receiver, including synchronization and equalization, counteracts almost all the degradation and interference of wireless channel. The outer receiver, composed of soft-decision Viterbi decoder as forward error control (FEC) using TCM, allows the full channel capacity to be approached. Also, our system gets better performance of power efficiency due to coherent detection instead of differential detection. Because of our software radio architecture, the programmability and efficient design effectively speed up the time to market. We provide a set of user-friendly application program interface (API) to facilitate application development. What is more important, our system has the rate-adaptive capacity to achieve the versatility, flexibility and adaptability under adverse environments in practical applications.

Our design is primarily based on the PHY specifications of ETSI HIPERLAN/2 and IEEE 802.11a. Because we focus mainly on constructing a prototype model, we adopt lower sample rate in our system. To bring about multirate OFDM, we use the same sample rate with different modulation and coding scheme. The locations of pilots are carefully designed to facilitate equalization of interpolation type. The specification of our system is shown in table 1.

The issue on synchronization can be further divided into four aspects: frame timing, carrier frequency, symbol timing and sampling clock synchronization. We adopt the sub-optimal algorithm based on MMSE criterion using repeated preamble patterns because it consumes reasonable processing power for us to handle. The pattern of the preamble with our creative design of inverse cyclic prefix and inverse cyclic

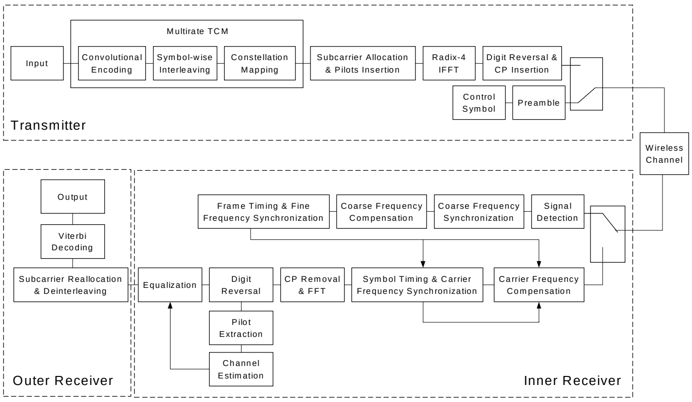

Figure 10. Block diagram of rate-adaptive OFDM

postfix is also adopted to better the performance of synchronization. In symbol timing stage, we exploit the optimal algorithm based on ML criterion and the information of CP and pilots. Besides, we add wake-up signals to suit our system designed for burst-mode transmission. The control symbol contains the necessary control information and the length of frame in an “octet” (means eight OFDM symbols).

Parameters	**Rate1** **1.5 Mbps**	**Rate2** **3 Mbps**	**Rate3** **4.5 Mbps**
Modulation	QPSK	16 QAM	16 QAM
Coding	1/2 TCM	1/2 TCM	3/4 TCM
FFT Point	64		
Sample Rate	2.5 Msample/sec		
OFDM Symbol Interval	32 μs		
Useful Data Duration	25.6 μs		
CP Period	6.4 μs		
Data Subcarriers	48		
Subcarrier Spacing	39.063 KHz		
Pilot Subcarriers	4		
Pilot Locations	$\pm 8^{th}$, $\pm 24^{th}$		
Occupied Bandwidth	2.075 MHz		

Table 1. Specifications of our designed OFDM system

In our design, channel estimation is designed to exploit the known pilots with interpolation technique. The algorithm we adopt is based on least square (LS) criterion. The reason we adopt it is that LS has comparative performance but less complexity. Also it can estimate the channel without knowing the channel characteristic in advance. After channel estimation is done with the aid of pilots and FFT, the equalization coefficients are then acquired and equalization can be thus achieved by multiplying the reciprocal of these coefficients.

We choose TCM rather than conventional convolutional (CC) code as FEC coding scheme to improve the receiver sensitivity. The soft-decision Viterbi decoder is implemented without trace-back steps to reduce complexity. The decoding length is taken as the number of data subcarriers for its suitability in our OFDM system. In addition, interleaving is used to overcome burst errors due to deep fading.

The hardware block diagram of our implementation is shown in Figure 11. And the software protocol hierarchy is shown in figure 12. We use DSP as the baseband processor to handle the issues of PHY, radio link control (RLC), and medium access control (MAC) sublayers. The host CPU as protocol processor covers the issues of upper layers. To facilitate the future development of application program, we establish OFDM API to hide the underlying operation.

About the code optimization and the upmost exploitation of TMS320C6201’s fixed-point architecture, we take many strategies to optimize the code and improve the overall performance since our high-speed system is time-critical. First of all, we set some parameters to optimize the compiler. In addition, we pay special attention to some details that can efficiently save cycles. For example, we choose the pilot pattern to be 1/-1 so that the operation of dividing by 1/-1 in channel estimation can be substituted for multiplication. The use of bit-wise XOR function combined with CC as shift register operation at the encoding stage enables parallelization and thus enlarges the throughput. The adoption of radix-4 64-point FFT/IFFT instead of radix 2 also reduces 27% execution time or so. Much processing power can be further saved when we make the best use of the fixed-point architecture of C6x. Multiplication and division can be operated in a more efficient way as well when the

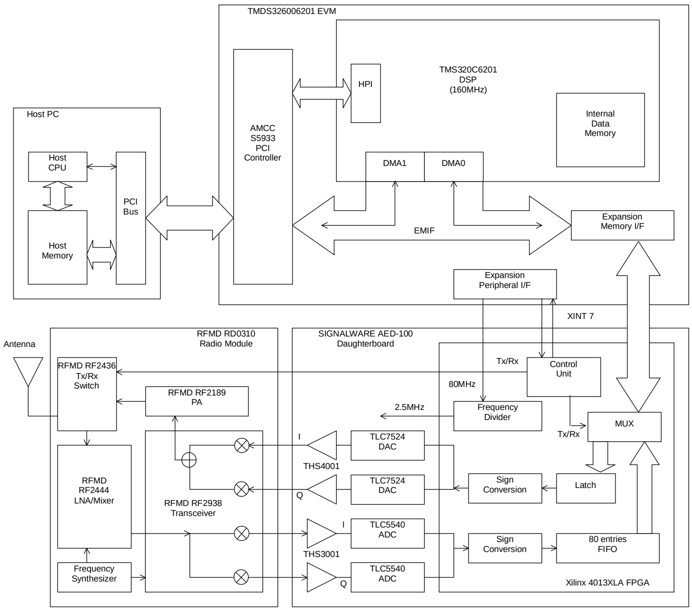

Figure 11. Hardware block diagram

multiplier or divisor is a 2’s exponent. When writing codes and constructing a table, we convert all the floating-point numbers to fixed-point ones in advance in order to ease the burden of the fixed-point DSP. This can surely enhance the speed of execution as long as each number is properly converted. The exploitation of tables is the most important feature to speed up the execution. Instead of calling time-consuming built-in functions, such as finding angle, sine/cosine, square root, and reciprocal, we construct corresponding look-up tables to speed up the execution, whose improvement is shown in Table 2.

Operation	Cycles of Built-in Functions	Cycles of Table Look-up	Reduction of loading by Table Look-up
Angle	3522	16	96.8%
Sine/Cosine	3211	7	99.8%
Square Root	82	12	85.4%
Reciprocal	51	7	86.3%

Table 2. Comparison of built-in functions and table look-up

四、計畫成果自評

A novel approach named MC-PDFD (multi-carrier parallel decision feedback decoder) to solve the problem of residual ISI is proposed in trellis-coded OFDM communication systems. MC-PDFD uses the immediate decision feedback stored in the trellis path history to remove the residual ISI terms in the received signal. Utilizing different feedbacks from the decoding trellis avoids the problem of error propagation in conventional decision feedback equalizers. Furthermore, MC-PDFD functions in this way that performs the tasks of equalization and trellis decoding simultaneously. Good performances of MC-PDFD are convinced by several simulation results with different subcarrier numbers, channel conditions, and trellis-coded modulation techniques. Issues of robustness and complexity of MC-PDFD are also discussed. The result shows that MC-PDFD can still have acceptable performance even without perfect channel estimation and the complexity of MC-PDFD is slightly increased compared to a conventional Viterbi decoder due to its ability to combat residual ISI and combine equalization and decoding altogether. Another important issue of large PAP ratio is also discussed. The related parameters that affect the value of PAP ratio is defined and the proper upper and lower bounds for different trellis-coded modulation schemes are derived. It is shown that using multi-dimensional trellis-coded modulation with OFDM systems is beneficial to lower PAP ratio because the constellation size of multi-dimensional trellis-coded scheme is smaller than that of 2-dimensional case. The difference of PAP ratio between multi-dimensional and 2-dimensional cases grows larger as the number of bits transmitted per signaling interval increases. Simulation results prove the accuracy of all derivations and inductions, which apply equally well to small subcarrier number and large subcarrier number.

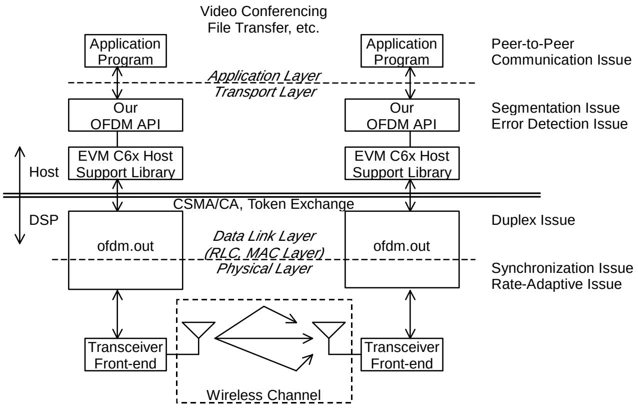

Figure 12. System protocol hierarchy

On the other hand, in this project, a complete peer-to-peer wireless communication system using OFDM is implemented. Rate-adaptability is achieved by examining the channel condition and switch to suitable modulation/coding scheme. A set of user-friendly API is provided at the host side to facilitate application development. The transmitter mode and the receiver mode utilize 26% and 97% of real-time DSP loading, respectively. If the soft-decision Viterbi decoder, which is the majority of receiver loading due to a great deal of memory access operation, can be implemented in off-the-shelf chip, the processing power of DSP can be used in more efficient way. Since our system can be upgraded to higher speed by increasing the sample rate and processor clock with little modification, our system can surely meet growing bandwidth needs and effectively reduce the time to market.

In summary, an OFDM system utilizing multi-dimensional trellis-coded modulation scheme and MC-PDFD can effectively solve the problem of residual ISI at the same time when trellis decoding is performed, with the lowest PAP ratio to achieve the best performance. And a rate-adaptive OFDM system is effectively designed and implemented. This programmable architecture shall provide a flexible implementation platform for future development of advanced OFDM systems.

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