RTT TECHNOLOGY TOPIC
May 2005

Adaptive Systems

In this month's Hot Topic we look at adaptive systems and their role in delivering power efficiency and bandwidth efficiency in wide area, local area and personal area radio networks.

There are two aspects to power efficiency. Firstly we have to produce power efficiently. This is driven by device geometry and in terms of processor bandwidth has depended on delivering an increasing number of clock cycles from a given area of silicon. Efficiency is however limited by leakage current, which increases as device geometry reduces.

This shifts the emphasis over time to using power efficiently particularly in compact hand held devices.

Adaptation is a technique increasingly applied at all points in the end to end channel to improve power utilisation efficiency. As such, it deserves our attention as a common denominator in 3G and 4G systems.

ADAPTIVE TECHNIQUES IN 3G AND 4G RADIO NETWORKS

Static and Dynamic Adaptation

There are two forms of adaptation, static adaptation and dynamic adaptation. Static adaptation, sometimes also described as static matching, is when a process such as source coding or channel coding is matched to a particular bandwidth requirement or channel condition. An example would be choosing to use 16 QAM or 64 QAM modulation in a DVB channel with a defined coding rate for a given type of service (standard or HDTV). Dynamic adaptation, sometimes also described as dynamic matching, is where a process such as source coding or channel coding changes potentially at every frame. Examples are 25 frame per second video in which the encoded data rate changes every 40 milliseconds, an AMR voice codec in which the encoded data rate changes every 20 milliseconds, an OVSF code channel in which the number of data bits in a frame changes every 10 milliseconds or an HSDPA channel in which the modulation and coding scheme changes every 2 milliseconds in response to a changed loading or channel requirement.

Table 1 Where adaptation is presently used or proposed

	Examples of adaptive source coding	Examples of adaptive processor bandwidth	Examples of adaptive modulation and channel coding (AMC)	Examples of adaptive(scaleable) radio bandwidth	Examples of adaptive network bandwidth
Text	ASCII/UCS2/UCS4	Adaptive voltage and frequency scaling	Adaptive modulation and coding Wide Area	Multiple PHY EDGE/HSDPA/WiFiBluetooth Scaleable OFDM	Mesh networks Ad Hoc networks
Data	Run length and Huffman coding				
Voice	Adaptive multi rate vocoders				
Audio	Audio AAC/AAC				

	Plus/MP3Pro		Local Area	WiMax, UWB	
Image	JPEG		WiFi		
Video	MPEG		Personal Area		
			Bluetooth and WiFi		

The table above introduces the areas where adaptation is presently used or proposed.

Source coding yields particular benefits when perceptual coding can be combined with predictive coding (voice, audio, image and video coding). Perceptual coding exploits the characteristics of the human audio system and human visual system to deliver 'perceived quality' at relatively low data rates. Predictive coding exploits block to block or frame to frame similarities. Both perceptual coding and predictive coding can be responsive (adaptive) to changes in audio or visual entropy. Adaptive multi rate vocoders are one example. There is a source coding 'gain effect' which is a composite of the compression and error concealment algorithms used in the coding process. The gain effect increases as entropy increases. In other words, it is particularly effective for audio, image and video processing. We discuss this in more detail below.

Adaptive processor bandwidth is based on the simple idea that voltages and clock rates can be matched to the particular tasks being performed at any particular time. Adaptive voltage and frequency scaling is used in an increasing number of hand held device processor chip sets and the techniques used are well documented and in the public domain. Frequency can be scaled in a few microseconds, voltage in a few tens of microseconds. Overall power saving can be significant though care has to be taken in the implementation of the policy control algorithms that drive the decision process. Adaptive voltage and frequency scaling is being combined with dual core and multi core processor architectures that can be optimised for adaptive multi tasking. Intel's recent announcements in this area are relevant.

Adaptive modulation and channel coding (AMC) is based on the principle that higher level modulation and lower level coding can be deployed adaptively as the radio link budget improves (the user moves closer to the base station). As with adaptive voltage and frequency scaling, care has to be taken with the implementation of the adaptation algorithms which themselves are dependent on accurate channel sounding (bit error probabilities in EDGE and channel information from the pilot symbols in CDMA and OFDM systems). Present examples of adaptive channel coding in wide area systems include EDGE (GMSK or 8 PSK), HSDPA (QPSK or 16 QAM and a 1/4, 2/4, 3/4 or 4/4 coding) and WiMax (QPSK, QAM or 64 QAM). In local area, WiFi (802.11 a and g) uses BPSK, QPSK, 16 QAM or 64 QAM. In personal area, Bluetooth (EDR) uses GFSK or 8PSK. Adaptive modulation and coding can be combined with scheduling algorithms, for example the 2 millisecond scheduling algorithms used in HSDPA, to maximise radio bandwidth efficiency (which translates into power efficiency).

Adaptive radio bandwidth is partly about implementing AMC and scheduling algorithms (see above) but is also increasingly a question of how to get multiple PHYS to work together at the same time. It is a non-trivial task to get an HSDPA transceiver to work simultaneously with a WiFi transceiver and a Bluetooth transceiver without compromising overall receive sensitivity. The contention based MACS used in present WiFi and Bluetooth implementations more or less guarantee that signals will collide.

Even with 40 dB of separation, the Bluetooth, WiFi and wide area radios will desensitise each other, wanted signals are often 70 to 80 dB below locally generated TX power levels, wide band noise from the TX side will add to the RX noise floor, reciprocal mixing will create cross modulation components.

Solving this PHY co existence issue is always going to be problematic, particularly if additional receive paths such as GPS (very noise sensitive) and DAB or DVB have to be accommodated. Present solutions tend to end up with multiple radio modules and far too many antennas. Managing the problem at the MAC layer however looks promising and will provide far more flexibility in the way that we use multiple radio access options.

Scaleable OFDM also opens up additional adaptive opportunities (see below).

Adaptive network bandwidth is partly about getting networks to behave predictably when exercised with highly asymmetric highly asynchronous traffic. Generally this can only be achieved by taking existing IP protocols and adjusting them to deliver ATM functionality. The implementation of fixed length IP packets provides one example. The adaptive network description can however also be applied to the mesh network and ad hoc protocols being increasingly persuasively promoted into areas such as WiMobile network deployment. Mesh network protocols become particularly useful at higher frequencies (for example above 11 GHz) where line of sight working is required.

ADAPTIVE AUDIO

We said earlier that adaptive audio source coding exploits the characteristics and limitations of the human audio system.

Adaptive audio coding is presently being implemented in two areas, spectral band replication and parametric stereo.

In spectral band replication, the audio encoder only encodes and transmits the lower part of a given amount of audio bandwidth together with some guidance information that allows the decoder to reconstruct the higher frequencies originally present in the signal. Spectral band replication can be used in narrow band signals to deliver a perceptual quality that is equivalent to analogue FM audio (with a 15 kHz frequency response). It can be used to replicate stereo quality that is equivalent to MP3 at over 100 kbps but at a channel rate of 64 kbps and can be used with mono, stereo or multi channel audio signals.

In parametric stereo, the encoder extracts a parametric representation of the stereo image of an audio signal and then transmits the signal in mono together with a 'parametric guidance' bit stream. The decoder regenerates the stereo signal from the mono signal by using the additional parametric information.

These techniques are used in the AAC Plus codec and in MP3PRO. AACPLus is specified as the high quality audio codec in 3GPP1 and 3GPP2. It is also used in Digital Radio Mondiale (see below) and DVB and is supported by the Internet Streaming Media Alliance. MP3Pro is supported in Win 32, Linux, Mac O/S, ARM, TI TriMedia decoders and Win 32, Linux and MAC O/S encoders.

Perceptual audio coding in combination with predictive audio coding techniques can be adaptive to the constantly changing entropy of an audio signal. This adaptability translates into bandwidth and power efficiency

ADAPTIVE VIDEO

Our eyes can adapt from a sunny day (150,000 lux) to a moonless overcast night (.0001 lux). We can adjust for colour temperature differences (auto white balance) from 2800 to 5500 Kelvin. We have the ability to adaptively process entropy in a fast moving scene. We have great pattern recognition skills (a face or shape in a crowd).

The image and visual processing chain in, for example, a camera phone with camcorder functionality has to emulate these capabilities.

Perceptual coding techniques exploit the limitations of our visual system. For example our inability to resolve fine detail after a scene change, our inability to resolve colour after a scene change, our relative inability to resolve fine diagonal detail. Present MPEG4 based macroblock based encoders provide a present example of adaptive perceptual and predictive coding. Wavelet based encoding techniques will provide additional perceptual and predictive source coding gain both in still image (JPEG) processing and MPEG coding schemes.

Perceptual coding and predictive coding in image and video processing can be adaptive to the constantly changing entropy in a scene. This adaptability translates into bandwidth and power efficiency.

ADAPTIVE RADIO BANDWIDTH AND THE ROLE OF SCALEABLE OFDM

Adaptive audio encoders and adaptive video encoding are used in a wide range of present broadcast and two way radio systems. Intuitively, these systems need to be adaptive in terms of their provisioning of radio bandwidth. Scaleable OFDM is presently being promoted as a mechanism for delivering flexible (ie adaptable) radio bandwidth. It is therefore useful to review present and proposed future OFDM systems.

The principle of all Orthogonal Frequency Division Multiplexed radio systems is to take a radio channel and create a number of discrete sub bands that are evenly spaced (orthogonal) from each other. Carrier demodulation is achieved by multiplying the carrier by a carrier of the same frequency and integrating the result. (The DFT/FFT transform). Some of the sub carriers are used to carry pilot symbols that are used to characterise the channel and help demodulation.

Scalability can be used to describe the ability of OFDM to be used at different frequencies (spectral or frequency scalability) and at different channel bandwidths (channel scalability). As we shall see below, OFDM can be found in radio systems working at below 30 MHz and radio systems working at up to 11 GHz. It can be found in radio systems with 5 Hz channel spacing and radio systems with 528 MHz of channel spacing. Scalability can also be used to describe the ability of a radio system to support a wide range of applications, for example wide area broadcast, 2 way wide area, local area and personal area.

WIDE AREA BROADCAST

Examples of OFDM used in wide area broadcast include DRM, DAB and DVB/DVB-H and Qualcomm's proprietary Media Flow.

DRM (Digital Radio Mondiale) uses an OFDM multiplex in the long, medium and short wave bands (below 30 MHz).

Table 2 OFDM in Digital Radio Mondiale

		Long wave 3 kHz to 300 kHz **Medium wave**	**Short wave** 3 MHz to 30 MHz	**Long wave** 3 kHz to 300 kHz **Medium wave** 300 kHz to 3000 kHz	**Short wave** 3 MHz to 30 MHz		

		300 to 3000 kHz					
		16 to 25 kbps FM mono quality		25 to 50 kbps FM stereo quality (48 kbps = CD quality)			
DRM Mode	Carrier Spacing	Number of sub carriers in a 9 kHz channel	Number of sub carriers in a 10 kHz channel	Number of sub carriers in a 18 kHz channel	Number of sub carriers in a 20 kHz channel	Symbol duration in milliseconds	Duration of guard interval
A	41.66 Hz	204	228	412	460	26.66 ms	2.66 ms
B	46.88 Hz	182	206	366	410	26.66 ms	5.33 ms
C	68.18 Hz		138		280	20.00 ms	5.33 ms
D	107.14 Hz		88		178	16.66 ms	7.33 ms

Mode A is used for medium wave and ground wave (long wave) propagation and carries more data as the propagation conditions are more benign (and therefore need less pilot symbol overhead). The other modes are used for short wave. The longer the guard interval, the more resilient the system will be to inter symbol interference. The present 9 kHz (long and medium wave) and 10 kHz (short wave) channels provide a channel rate of between 16 and 25 kbps using QAM modulation. An MPEG4 CELP codec is used for speech and an AAC Plus codec is used to provide perceived quality that is equivalent to a 15 kHz FM broadcast. The voice and audio streams can be combined with text, data and images (like DAB or FM based visual radio). The wider channel bandwidths are not presently supported but could theoretically deliver CD quality sound at 48 kbps.

Additional information on DRM can be found at www.drmradio.co.uk and www.drm.org

Table 3 OFDM in DAB

Mode	Number of sub carriers in a 1.536 MHz channel	Carrier spacing	Symbol duration in milliseconds	Guard interval in milliseconds
A	1536	1 kHz	1.246 ms	0.246 ms
B	768	2 kHz	0.623 ms	0.123 ms
	512	3 kHz	0.467 ms	0.0922 ms
C	384	4 kHz	0.312 ms	0.062 ms
	256	6 kHz	0.234 ms	0.046 ms
D	192	8 kHz	0.156 ms	0.031 ms

DAB can be used in the FM VHF band (88 MHz to 108 MHz), at 220 MHz (the old Band 3 black and white TV transmission frequency) and L Band (1452 to 1492 MHz). DAB is implemented in the UK at 220 MHz. Most receivers are dual band (Band 3 and L Band). The system uses QPSK modulation. The gross stereo and 24 kbps data channels or any mix of channels between 48 kbps and 256 kbps. Additional information is available at www.dab.org

DVB and DVB H is similar to DAB in terms of symbol duration and guard interval but has the option of being implemented with QPSK, 16 QAM or 64 QAM modulation and different levels of channel coding.

As table 4 shows, these higher order modulation schemes require significantly more received signal level.

Table 4 DVB-T Modulation, Coding and Link Budgets

DVB-T 2K (2000 sub carriers)					DVB-T 8K (8000 sub carriers)	
	Modulation	Code rate	C/I needed at failure threshold	Data rate	Modulation	Data rate
A	QPSK	1/2	12 dB	12 mbps	QPSK	10.6 mbps
B	16 QAM	3/4	16.5 dB	18 mbps	16 QAM	21 mbps
C	64 QAM	2/3	20 dB	24 mbps	64 QAM	30 mbps

DVB-H has the same choice of modulation and coding but time slices the signal (to reduce the power budget in the receiver and to realise a simultaneous multiplex with the DVB-T signal). DVB-H 8K OFDM is the same as DVB-T (8000 sub carriers spaced at 1 kHz within an 8 MHz channel). There is also a 4K DVB-H OFDM with sub carriers spaced at 2 kHz and a 2K OFDM with sub carriers spaced at 4 kHz and the additional option of a 5MHz rather than 8 MHz channel. More information on DVB is available at www.dvb.org

Qualcomm's Media Flow uses similar time slicing techniques to DVB-H but the receiver soft combines common packets received from multiple cell sites. The OFDM FFT slows down the symbol rate to simplify the soft combining.

TWO WAY OFDM (Local area/WiFi)
802.11 a and g use 20 MHz channels within the 2.4 GHz (g) or 5 GHz (a) ISM bands. There are 64 OFDM sub carriers consisting of 48 data carriers and 4 pilot sub carriers each spaced 312.5 kHz apart.

Table 5 WiFi 802.11 a and g Adaptive Modulation and Coding

Data rate	6/9 Mbps	12/18 Mbps	24/36 Mbps	48/54 Mbps
Modulation	BPSK	QPSK	16 QAM	64 QAM
Code rate	1/2 or 2/3 or 3/4			

Table 5 shows how gross data rates up to 54 Mbps are supported in terms of adaptive modulation and coding. A 54 Mbps channel using 64 level QAM has a symbol rate of 4 microseconds and a guard interval of 0.8 microseconds. Given that radio waves take 0.33 microseconds to travel 100 meters, the 0.8 microseconds of guard band is sufficient for the amount of delay spread that is likely to occur in a local area network. In a wide area broadcast system, the delay spread will of course be much larger, hence the need for longer guard bands. More information on WiFi is available at www.wi-fi.org

TWO WAY OFDM (Wide Area/WiMax,WiMobile)
The original 802.16 air interface intended for use between 11 GHz and 66 GHz for line of sight applications supports data rates of between 32 and 134 Mbps in a 28 MHz channel with QPSK, QAM or 64 QAM modulation.

The 802.11 d air interface is intended for use between2 and 11 GHz for non line of sight supporting up to 75 Mbps in a 20 MHz channel with QPSK, QAM or 64 QAM and a 256 carrier OFDM. 802.11d plus adds QoS support.

802.11 e also known as WiMobile, has the same three modulation options but can either have a 512 FFT (512 OFDM sub carriers) occupying a 5 MHz channel or a 1024 FFT occupying a 10 MHz channel or a 2048 FFT occupying a 20 MHz channel. The 5 MHz channel is claimed to support data rates of up to 15 Mbps. WiMobile uses a hybrid ARQ similar to HSDPA and will (probably) use mobile IP protocols to manage cell to cell mobility.

WiMax can be deployed into either FDD (paired frequency bands) or TDD (time division duplexed) spectrum.

More information on WiMax and WiMobile is available at www.wimaxforum.org

Two Way OFDM (Local area/ Multi Band OFDM UWB)

Multi band OFDM is one of two air interfaces presently proposed for ultra wide band (UWB) systems for use between 3.1 and 10.6 GHz (the other being direct sequence UWB). The multi band OFDM splits the radio spectrum from 3.432 to 10.296 GHz into 14 separate UWB channels each of 528 MHz. Each 528 MHz channel has 128 OFDM sub carriers spaced 4.125 MHz apart. Gross data rates go from 53.3 Mbps to 480 Mbps (for high-speed wireless UWB USB) and the coding options are either 1/3, 11/32, 1/2, 5/8 or 3/4. Modulation is QPSK. More information on multi band OFDM is available at www.multibandofdm.org

SCALEABLE OFDM SYSTEM OPTIONS

Table 6 summarises the present range of 'scaleable' OFDM system options.

Area	Broadcast Wide Area			2 Way Local Area	2 Way Wide area	2 Way Wide Area Nomadic or mobile			Personal Area Multiband OFDM
Frequency	<30 MHz	100MHz 220MHz 1400 MHz	700 MHz	2.4 and 5 GHz	2 to 11 GHz	2 to 11 GHz			3 to 11 GHz
System	DRM	DAB	DVB	WiFi	WiMax	WiMobile			Multiband OFDM
Range	500 km	100 km	100 km	100 m	2-5 km	2-5 km			1-10m
Max gross data rates	25 kbps	2.304 mbps	30 mbps	54 mbps	75 mbps	15 mbps			480mbps
Channel bandwidth	9 KHz	1.536 MHz	5,6,7 or 8 MHz	20 MHz	20/28 MHz	5 MHz	10 MHz	15 MHz	528 MHz
Modulation	QAM	QPSK	QPSK, 16 QAM	BPSK, QPSK	QPSK 16 QAM	QPSK 16 QAM			QPSK

			64 QAM	16 QAM 64 QAM	64 QAM	64 QAM				
Number of sub carriers	204	1536	8000	64	256	512	1024	2048	128
Sub carrier spacing	41.66 Hz	1 kHz	1 kHz	312.5 kHz	78.125 kHz	10 kHz	20 kHz	30 kHz	4.125 MHz
Symbol duration	26.66 ms	1.246 ms	1.246 ms	4 micro seconds	16 micro seconds	204 micro seconds	408 micro seconds	816 micro seconds	312.5 nano seconds
Guard interval	2.66 ms	0.246 ms	0.246 ms	0.8 micro seconds	3.2 micro seconds	40.8 micro seconds	81.6 micro seconds	163.2 micro seconds	9.5 nano seconds

As the table shows, OFDM is used at frequencies from 30 MHz to 10 GHz, with cell sizes ranging from several hundred kilometres to under a meter and data rates of 25 kbps to 480 Mbps. Channel bandwidths range from 9 kHz to 528 MHz. Modulation can be anything from QPSK to 64 QAM and the OFDM multiplex can be as simple as 64 sub carriers or as complex as 8000 sub carriers with sub carrier spacing of between 41.66 Hz and 4.125 MHz.

The symbol duration and guard periods are determined by channel conditions and application requirements. Slower symbol rates and longer guard periods help to minimise inter symbol interference in a multi path channel (resilience to delay spread) but narrow sub carrier spacing can make the radio signal sensitive to Doppler spread. As we said in our December 2004 Hot Topic (OFDM Performance and Cost Implications) there are some significant practical design issues associated with PFDM transceivers. Closely spaced sub carriers amplify the effects of non linearity and VCO instability. Transmitter modulation accuracy can be compromised by constellation errors, centre frequency leakage and a lack of spectral flatness. The significant peak to average amplitude in the modulated waveform can cause compression and non-linear effects. Problems with modulation quality either show up as an error vector at sub carrier level or at symbol level and are typically caused by PA non linearity, signal clipping, signal filtering or phase noise. All these factors can conspire together to limit practical transceiver performance in terms of receive sensitivity which in turn can translate into disappointing real life throughput.

So OFDM is adaptive and scaleable but is it power efficient?
Taking some of the performance issues outlined above into account, the answer is not really just yet. The broadcast OFDM systems (DRM, DAB, DVB-H and Media Flow) support reasonably power efficient receivers which can look attractive from a power budget perspective when compared to other options (such as the delivery of TV or audio over HSDPA channels). Putting OFDM transmitters into small hand held form factor phones (for example WiFi into cell phones) is however still relatively expensive in terms of overall power drain. This is however changing as design techniques improve.

SUMMARY

Adaptive techniques are increasingly used at all points in the end to end channel to realise bandwidth and power efficiency benefits. Examples of adaptive radio bandwidth include multiple PHY implementations and scaleable OFDM. Scaleable OFDM has not to date realised significant gains in terms of power efficiency but the overall system benefits achievable at system level suggest that OFDM will become increasingly pervasive in wide area, local area and personal area networks.

About RTT Technology Topics

RTT Technology Topics reflect areas of research that we are presently working on.

We aim to introduce new terminology and new ideas to clarify present and future technology and business issues.

Do pass these Technology Topics on to your colleagues, encourage them to join our Push List and respond with comments.

Contact RTT

RTT, the Shosteck Group and The Mobile World are presently working on a number of research and forecasting projects in the cellular, two way radio, satellite and broadcasting industry.

If you would like more information on this work then please contact

geoff@rttonline.com

00 44 208 744 3163