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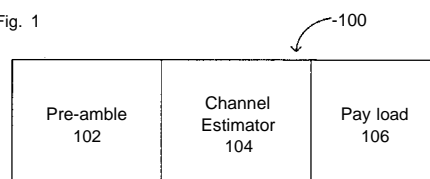
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(54) Title: ESTIMATION OF SIGNAL TO NOISE RATIO IN RECEIVERS

Fig. 1



(57) Abstract: This invention concerns the estimation of signal to noise ratio (SNR) at a communications receiver; it may be applicable to a wide range of receivers but is particularly suited for Orthogonal Frequency Division Multiplexing (OFDM) receivers. In particular the invention is a method, a receiver and software for performing the method. The signal to noise ratio (SNR) in the received signals is estimated by directly estimating the power ratio, in the received signal, between the part of the frequency spectrum of the received signal that contains only noise, and the part of the spectrum that contains both signal and noise; and averaging this value over a time interval.



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## **Estimation of Signal to Noise Ratio in Receivers**

### **5 Technical Field**

This invention concerns the estimation of signal to noise ratio (SNR) at a communications receiver; it may be applicable to a wide range of receivers but is particularly suited for Orthogonal Frequency Division Multiplexing (OFDM) receivers.

- 10 In particular the invention is a method, a receiver and software for performing the method.

### **Background Art**

- 15 The invention will be described primarily in the context of Orthogonal Frequency Division Multiplexing (OFDM) which is the dominant multiplexing and modulation technique used in wireless communications. OFDM transmits multiple data streams by assigning each of them uniquely to one or more of a large number of sub-carriers where each sub-carrier operates at a unique carrier frequency (tone). The adjacent sub-carrier
- 20 frequencies or tones have a fixed frequency difference between them. The data is carried in each sub-carrier by modulating its amplitude or phase, or both. In practice many of the sub-carriers are not used, typically the unused sub-carriers include a small number at the centre of the transmission band, and a block at both edges of the transmission band.

25

At the transmitter (TX), OFDM enables the efficient use of the available channel bandwidth and the easy control of the signal spectrum mask.

- At the Receiver (RX), OFDM allows simple equalization and is robust to constant
- 30 timing offset due to the adoption of a Cyclic Prefix (CP) in the transmission. However, to optimize the system performance, the receiver is often required to estimate the signal

to noise ratio (SNR). For instance, knowledge of the SNR is useful for clear channel assessment, soft-decision channel decoding, Transmitter power control, adaptive coding and modulation, bit loading and hand-off.

- 5 SNR estimation has been investigated, especially in the context of single carrier (SC) modulation schemes [1-4]. Some of the SC SNR estimation schemes can be directly adapted to OFDM modulation [5], and these can be classified into two broad categories:
- 10 data-aided (DA), and  
non-data-aided (NDA), which are also called "blind" schemes.

Data-aided schemes require some known data to be transmitted, for example, in some preselected pilot subcarriers in the Payload field. Alternatively, one or more training OFDM symbols can be transmitted in the Preamble or the Channel Estimation fields.

- 15 OFDM SNR estimation schemes can further be divided into time-domain (TD) and frequency-domain (FD) processing algorithms.

References [6-9] describe known blind OFDM SNR estimation algorithms that can be applied to the Payload field without the requirement of preselecting the pilot

- 20 subcarriers. The time domain signal during the Cyclic Prefix (CP) interval and towards the end of the OFDM symbol are highly correlated. In [6, 7], this correlation is used for SNR estimation. The disadvantage of this approach is that the number of useable samples in one OFDM symbol is very small due to the fact that most of the CP interval is interfered by the previous OFDM symbol. As a result a large number of OFDM
- 25 symbols are needed to achieve accurate estimation.

By assuming that the signal and noise covariance matrices are different and known, a Maximum-Likelihood (ML) method with high computational complexity is proposed in [8].

30

The expectation maximization (EM) algorithm is used in [9]. However, the algorithm

assumes knowledge of the channel and is therefore dependent on channel estimation accuracy.

### **Disclosure of the Invention**

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The invention is a method for estimating the Signal to Noise Ratio (SNR) of received RF signals, including those having multiple sub-carriers, comprising:

Converting the analogue RF signal to digital samples at a sampling frequency that is more than twice the RF signal bandwidth.

10 Transforming the digital signal to the frequency domain.

Estimating the power of some or all of the signal samples in the frequency domain.

Estimating the signal to noise ratio of the received signal, or of selected samples of the received signal, from the ratio of:

The power of samples that include signal plus noise, or the selected samples of them,

15 and

The power of samples that include noise only; that is those signals outside the signal bandwidth but within the system bandwidth.

The ratio may be averaged over a selected time interval, and the samples that include

20 signal plus noise may also be selected to estimate the signal to noise ratio per band, packet, sub-packet or sub-carrier of the received signals.

The Noise to Noise Ratio (NNR)  $\eta$  of the noise in the noise only samples, and the signal plus noise sub-carriers may also be calculated, so that the signal to noise ratio

25 can be properly scaled.

This method provides for generic, low-complexity, blind SNR estimation that is independent of the characteristics of the signal and the channel; and can be used for all OFDM and SC signals.

30

When the received RF signal includes multiple sub-carriers, the method may comprise:  
Sampling the received signals by analogue to digital converters (ADC), with a  
sampling frequency that is more than twice the signal bandwidth.

Performing a fast Fourier transform (FFT) on a block of samples to derive the values of  
5 each subcarrier.

Estimating the power of each received sub-carrier of the received RF signals.

Calculating the Noise to Noise Ratio (NNR)  $\eta$ , of the noise in the noise only sub-carriers and the signal plus noise sub-carriers.

Calculating the estimated Signal to Noise Ratio  $\hat{\psi}$  as follows:

10

$$\hat{\psi} = \frac{\sum_{j \in J} \sum_{k \in K} |Y(j, k)|^2}{\sum_{j \in J} \sum_{q \in Q} |Y(j, q)|^2} \eta - 1$$

Where  $|Y(j, k)|$  represents the amplitude of the signal carried by each of  $K$  sub-carriers  
carrying signal plus noise, and  $j$  represents each of  $J$  instants.

15 and

Where  $|Y(j, q)|$  represents the amplitude of the signal carried by the sub-carriers  
carrying no signal (noise only), and  $j$  represents each of  $J$  instants.

The estimated Signal to Noise Ratio  $\hat{\psi}$  may be calculated as follows:

20 First, calculating the sum of the square amplitudes of the signals in the sub-carriers carrying signals (signal plus noise).

Next, calculating the sum of the square amplitudes of the signal in the sub-carriers carrying no signal (noise only).

Next, summing the sum of the square amplitudes of the signals in the sub-carriers carrying signals (signal plus noise) at each instant  $j$  over a time interval  
25  $J$  to produce a first summation.

Next, summing the sum of the square amplitudes of the signals in the sub-carriers carrying no signal (noise only) at each instant  $j$  over a time interval  $J$  to

## 5

produce a second summation.

Then, taking the ratio of the first and second summations, multiplying by the Noise to Noise ratio (NNR)  $\eta$ , and subtracting 1.

- 5 The method can be applied over only part of the signal spectrum (that contains both signal and noise) which allows an estimate of SNR for only part of the spectrum, such as a band, packet or subcarrier.

For colored noise, the Noise to Noise Ratio (NNR) may be calculated as follows when

- 10 the transmitter is turned off:

Summing the estimated power of each sub-carrier within the signal bands of the received RF signals to produce a first sum.

Summing the estimated power of each sub-carrier within the noise only bands of the received RF signals to produce a second sum.

- 15 Summing the value of each of the first sums calculated at different instants over a first time interval to produce a third sum.

Summing the value of each of the second sums calculated at different instants over the first time interval to produce a fourth sum.

Calculating the ratio of the third and fourth sums.

20

For white noise, the NNR is a known constant:

$$\eta = 1 + \frac{1}{N} \sum_{i=1}^N K_i$$

where  $\|\bullet\|$  represents the number of subcarriers in the respective set.

- 25 The method may be applied with any type of noise, such as white noise, Gaussian noise or coloured noise..

The Signal to noise ratio estimated by use of the method, may be used at the receiver to improve performance; such as Automatic Gain Control (AGC), Automatic Frequency

- 30 Control (AFC), adaptive filtering or channel estimation.

Alternatively the Signal to noise ratio estimated by use of the method, may be fed back to the transmitter to improve performance; such as adaptive channel and carrier frequency selection.

- 5 In some situations of colored noise/interference it may be useful to switch off the transmitter at the end of the preamble for a short time to allow the receiver to estimate the Noise to Noise Ratio and adjust its other receiver parameters such AGC gains and carrier frequencies.

- 10 The method is independent of the characteristics of the signal and the channel. Therefore the proposed SNR estimation method may be applied to any signal constellation.

- 15 The proposed method is also equally applicable to frequency selective and fading channels.

Sometimes only the estimation of the noise variance (rather than the SNR) is required. Alternatively, the means square error (MSE) or the normalized MSE of the SNR estimate can be used.

- 20 The impact of wideband interference can be treated the same as noise. However, the method is more applicable to scenarios where the interference has wider bandwidth than the target signal so that the interference occurs at both data subcarriers and the guard-band subcarriers. For example, a Wi-Fi receiver can use this method to measure  
25 the interference from ultra-wideband radios.

- The proposed method does not require the existence of virtual subcarriers in the transmitter on which no signal is transmitted. However, almost all practical OFDM systems have guard-band virtual subcarriers towards the ends of the channel  
30 bandwidth. In the event all subcarriers were used for data and pilot signals, the receiver can adopt an oversampling strategy to make use of the proposed method. After over-

sampling, it is expected that the signal is concentrated in the middle of the spectrum while the noise falls into the whole spectrum.

- In a second aspect, the invention is a communications receiver with the ability to
- 5 estimate the signal to noise ratio (SNR) in the received signals by directly estimating the power ratio, in the received signal, between the part of the frequency spectrum of the received signal that contains only noise, and the part of the spectrum that contains both signal and noise; and averaging this value over a time interval.
- 10 In a third aspect, the invention is software for performing the method.

### **Brief Description of the Drawings**

- An example of the invention will now be described with reference to the accompanying
- 15 drawings, in which

Fig. 1 is diagram of the structure of a generic data packet in the time domain.

Fig. 2 is a frequency domain diagram of the generic data packet.

- 20 Fig. 3 is a flow diagram of the process of estimating the signal to noise ratio of the received signal.

Fig. 4 is a block diagram of a receiver implementing the process of Fig. 3.

- 25 Fig. 5 is a block diagram of a receiver implementing the process.

### **Best Modes of the Invention**

- 30 The format of a generic OFDM or SC communications packet 100 is shown in Fig. 1.



## 8

The packet has three fields: Preamble 102, Channel Estimation (CE) 104 and Payload 106. The preamble 102 enables the receiver (RX) to reliably detect the arrival timing of the packet, and to estimate and correct the carrier frequency offset. The Channel Estimation (CE) field 104 allows the channel to be estimated so that a time-domain or  
5 frequency-domain equalization can be easily performed to decode the Payload field. The Payload 106, in the case of OFDM, comprises a string of OFDM symbols

In the frequency domain of the received sampled sequence with a sampling frequency more than two times of the signal bandwidth, almost all practical OFDM and SC  
10 systems define a set of subcarriers on which no signal is transmitted. These empty carriers are normally located at the two ends of the channel bandwidth. As a result the transmitted OFDM and SC data packets 106 have a signal bandwidth 200, and a noise bandwidth 202 that is wider than the signal bandwidth 200; see Fig. 2.

15 Of course there is noise within the signal bandwidth as well as signal, but outside of the signal bandwidth there are two frequency sub-bands 204 and 206 that contain only noise.

Referring now to Figs. 3 and 4, the process 300 and additional hardware required 400  
20 to estimate the signal to noise ratio will now be described in the context of an OFDM receiver.

First it is necessary to receive the Radio Frequency (RF) transmitted signal and demodulate it 302; for instance using an RF receiver and demodulator 402.

25 Then it is necessary to sample the demodulated analogue signal to digitize it 304; for instance using an Analogue to Digital Converter (ADC) 404. The result is a series of digital samples.

30 The symbol boundaries are then determined using a time synchronization of the digital samples 306, 406.

Then, frequency correction takes place 308 by means of a frequency synchronization 408.

- 5 The resulting digital signal is then transformed to the frequency domain 310, for instance using the Fast Fourier Transform, 410.

In the frequency domain it is then possible to estimate the power 312 of each received sub-carrier, for instance using spectrum analysis 412.

10

Then the Noise to Noise Ratio (NNR) of the noise in the noise only sub-carriers and in the signal plus noise sub-carriers is calculated 324 as follows:

The instantaneous Noise to Noise Ratio (NNR) of colored noise, at any instant when is

- 15 TX is not transmitting is calculated from:

The sum of the estimated power of each sub-carrier  $k$  within the signal bandwidth 200; that is:

$$20 \quad \sum_{k \in K} |N(j, k)|^2 \quad 320$$

Divided by the sum of the estimated power of each sub-carrier  $q$  across the noise only bands 204 and 206. That is:

$$25 \quad \sum_{q \in Q} |N(j, q)|^2 \quad 322$$

Over time an average for the Noise to Noise ratio (NNR)  $\eta$  is given by summing each of the instantaneous NNRs over a time interval  $J$  comprising  $j$  instances:

10

$$\eta = \frac{\sum_{j \in J} \sum_{q \in Q} |N(j, q)|^2}{\sum_{j \in J} \sum_{k \in K} |N(j, k)|^2} \quad 324$$

Using the NNR it is then possible to calculate an estimated Signal to Noise Ratio (SNR) from the amplitude of the signal in each sub-carrier in the received signal as follows:

First, calculating the sum of the square amplitudes of the signals in the sub-carriers carrying signals (signal plus noise):

$$\sum_{k \in K} |Y(j, k)|^2 \quad 26$$

Next, calculating the sum of the square amplitudes of the signal in the sub-carriers carrying no signal (noise only):

$$\sum_{q \in Q} |Y(j, q)|^2 \quad 328$$

Next summing the sum of the square amplitudes of the signals in the sub-carriers carrying signals (signal plus noise) at each instant  $j$  over a time interval  $J$ :

$$\sum_{j \in J} \sum_{k \in K} |Y(j, k)|^2 \quad 330$$

Next summing the sum of the sum of the square amplitudes of the signals in the sub-carriers carrying no signal (noise only) at each instant  $j$  over a time interval  $J$ :

$$\sum_{j \in J} \sum_{q \in Q} |Y(j, q)|^2 \quad 332$$

## 11

Then taking the ratio of 330 and 332, multiplying by the Noise to Noise ratio (NNR)  $\eta$ , and subtracting 1:

$$\hat{\psi} = \frac{\sum_{j \in J} \sum_{k \in K} |Y(j, k)|^2}{\sum_{j \in J} \sum_{q \in Q} |Y(j, q)|^2} \eta - 1$$

334

5

These calculations are performed using an SNR estimator module 424.

It is a trivial matter to extend the method to multiple-input multiple-output (MIMO) OFDM and MIMO SC systems. The algorithm can be used directly before or after the MIMO equalizer. When used before the MIMO equalizer the SNR for a particular receiver can be measured. The MIMO equalizer resolves the MIMO channel into multiple independent channels, and the SNR on each resolved channel can thus be measured.

15 Referring now to Fig. 5, the architecture of a receiver that implements the invention will now be described:

In general the receiver has the same organization as the more general receiver shown in Fig. 4. RF chip 502 manages the reception and demodulation of the RF signal. The high speed ADC 504 samples the analogue input signal for conversion to digital form. After conversion to the frequency domain 510, the Signal to noise ratio is developed 524.

Finally, the method may be used in Single Carrier (SC) systems. In this case the received signal is first over-sampled and then a sequence of samples is converted to the Frequency Domain by fast Fourier transform (FFT). In the FD, it is expected that the signal is concentrated in the middle of the spectrum while the noise falls into the whole spectrum as shown in Fig. 2.

25

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**Claims**

1. A method for estimating the Signal to Noise Ratio (SNR) of received RF  
5 signals, comprising:  
converting the analogue RF signal to digital samples at a sampling frequency that is more than twice the RF signal bandwidth;  
transforming the digital signal to the frequency domain;  
estimating the power of some or all of the signal samples in the frequency domain;  
10 estimating the signal to noise ratio of the received signal, or of selected samples of the received signal, from the ratio of:  
the power of samples that include signal plus noise, or the selected samples of them, and  
the power of samples that include noise only.  
15
2. A method according to claim 1, applied to RF signals having multiple sub-carriers, wherein the ratio of:  
the power of samples that include signal plus noise, or the selected samples of them, and  
20 the power of samples that include noise only;  
is averaged over a selected time interval, and the samples that include signal plus noise are selected to estimate the signal to noise ratio per band, packet, sub-packet or sub-carrier of the received signals.
- 25 3. A method according to claim 2, wherein the Noise to Noise Ratio (NNR)  $\eta$  of the noise in the noise only samples, and the signal plus noise sub-carriers is calculated, so that the signal to noise ratio can be properly scaled.

4. A method according to claim 3, comprising:  
 estimating the power of each received sub-carrier of the received RF signals;  
 calculating the Noise to Noise Ratio (NNR)  $\eta$ , of the noise in the noise only  
 sub-carriers and the signal plus noise sub-carriers;  
 5 calculating the estimated Signal to Noise Ratio  $\hat{\psi}$  as follows:

$$\hat{\psi} = \frac{\sum_{j \in J} \sum_{k \in K} |Y(j, k)|^2}{\sum_{j \in J} \sum_{q \in Q} |Y(j, q)|^2} \eta - 1$$

where  $|Y(j, k)|$  represents the amplitude of the signal carried by each of  $K$  sub-carriers  
 and  $j$  represents each of  $J$  instants.

10

5. A method according to claim 4, wherein the estimated Signal to Noise Ratio  $\hat{\psi}$   
 is calculated as follows:

first, calculating the sum of the square amplitudes of the signals in the sub-  
 carriers carrying signals (signal plus noise);

15

next, calculating the sum of the square amplitudes of the signal in the sub-  
 carriers carrying no signal (noise only);

next, summing the sum of the square amplitudes of the signals in the sub-  
 carriers carrying signals (signal plus noise) at each instant  $j$  over a time interval  
 $J$  to produce a first summation;

20

next, summing the sum of the square amplitudes of the signals in the sub-  
 carriers carrying no signal (noise only) at each instant  $j$  over a time interval  $J$  to  
 produce a second summation;

then, taking the ratio of the first and second summations, multiplying by the  
 Noise to Noise ratio (NNR)  $\eta$ , and subtracting 1.

25

6. A method according to claim 4, wherein the Noise to Noise Ratio (NNR) for  
 colored noise is calculated as follows when the transmitter is turned off:  
 summing the estimated power of each sub-carrier within the signal bands of the  
 received RF signals to produce a first sum;

summing the estimated power of each sub-carrier within the noise only bands of the received RF signals to produce a second sum;

summing the value of each of the first sums calculated at different instants over a first time interval to produce a third sum;

- 5 summing the value of each of the second sums calculated at different instants over the first time interval to produce a fourth sum; and  
calculating the ratio of the third and fourth sums.

7. A method according to claim 4, wherein for white noise, the Noise to Noise  
10 Ratio (NNR) is a known constant given by :

$$\eta = 10 \log_{10} (N / M) \text{ dB}$$

where  $N$  represents the number of subcarriers in the respective set.

8. A method according to claim 4, wherein the Signal to noise ratio estimated by  
15 use of the method, is used at the receiver to improve performance, including Automatic Gain Control (AGC), Automatic Frequency Control (AFC), adaptive filtering or channel estimation.

9. A method according to claim 4, wherein the Signal to noise ratio estimated by  
20 use of the method, is fed back to the transmitter to improve performance, including adaptive channel and carrier frequency selection.

10. A method according to claim 4 including the further step of switching off the transmitter at the end of the preamble for a time to allow the receiver to estimate the  
25 Noise to Noise Ratio.

11. A method according to claim 10, comprising the further step of leaving the transmitter off until the receiver has adjusted other parameters, including AGC gains and carrier frequencies.

30

12. A method according to claim 1, applied to the estimation of the noise variance,



the means square error (MSE) or the normalized MSE of the SNR estimate, rather than the signal to noise ratio.

13. A communications receiver with the ability to estimate the signal to noise ratio
- 5 (SNR) in the received signals by directly estimating the power ratio, in the received signal, between the part of the frequency spectrum of the received signal that contains only noise, and the part of the spectrum that contains both signal and noise; and averaging this value over a time interval.
- 10 14. Software for performing the method of claim 1.

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Fig. 1

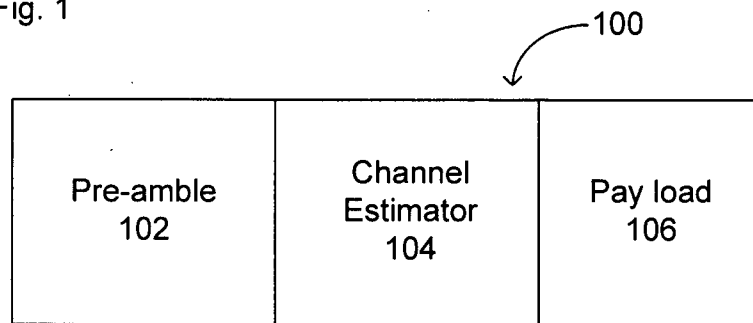
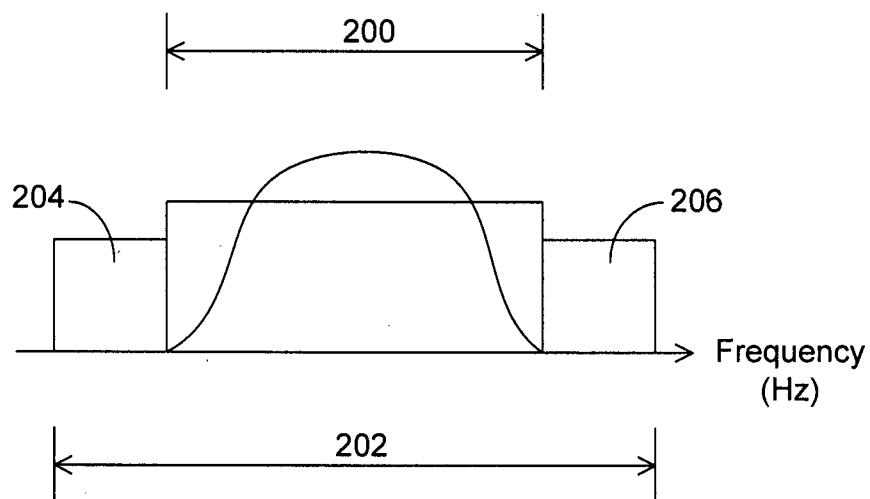
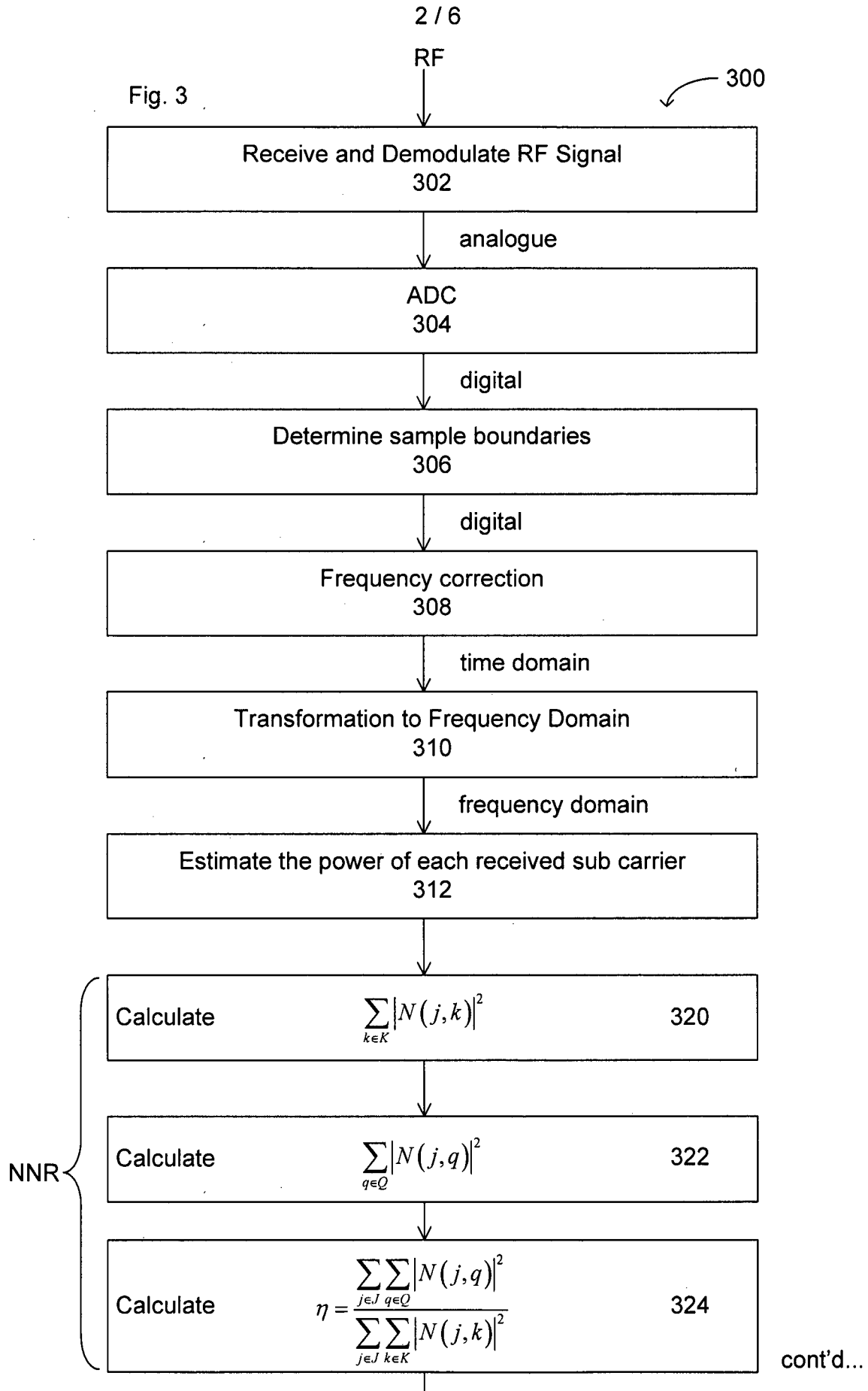


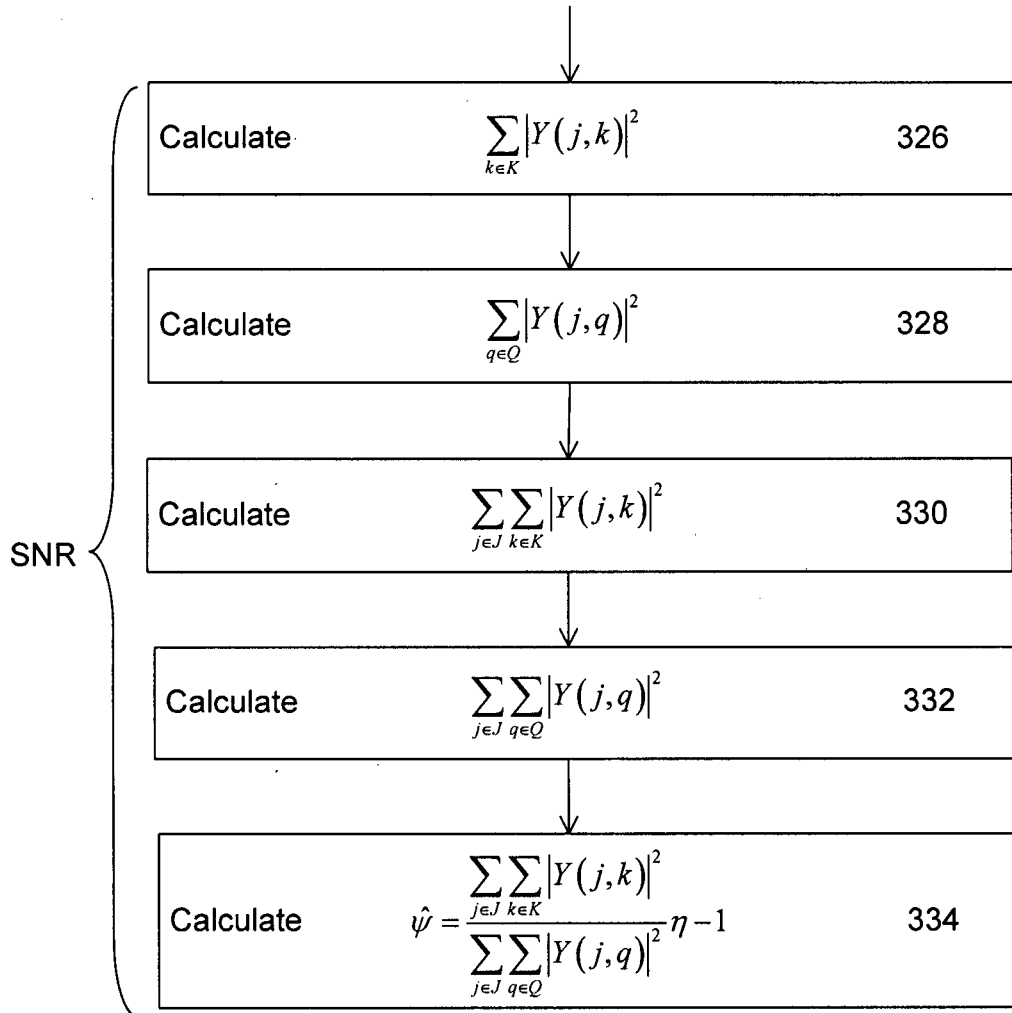
Fig. 2





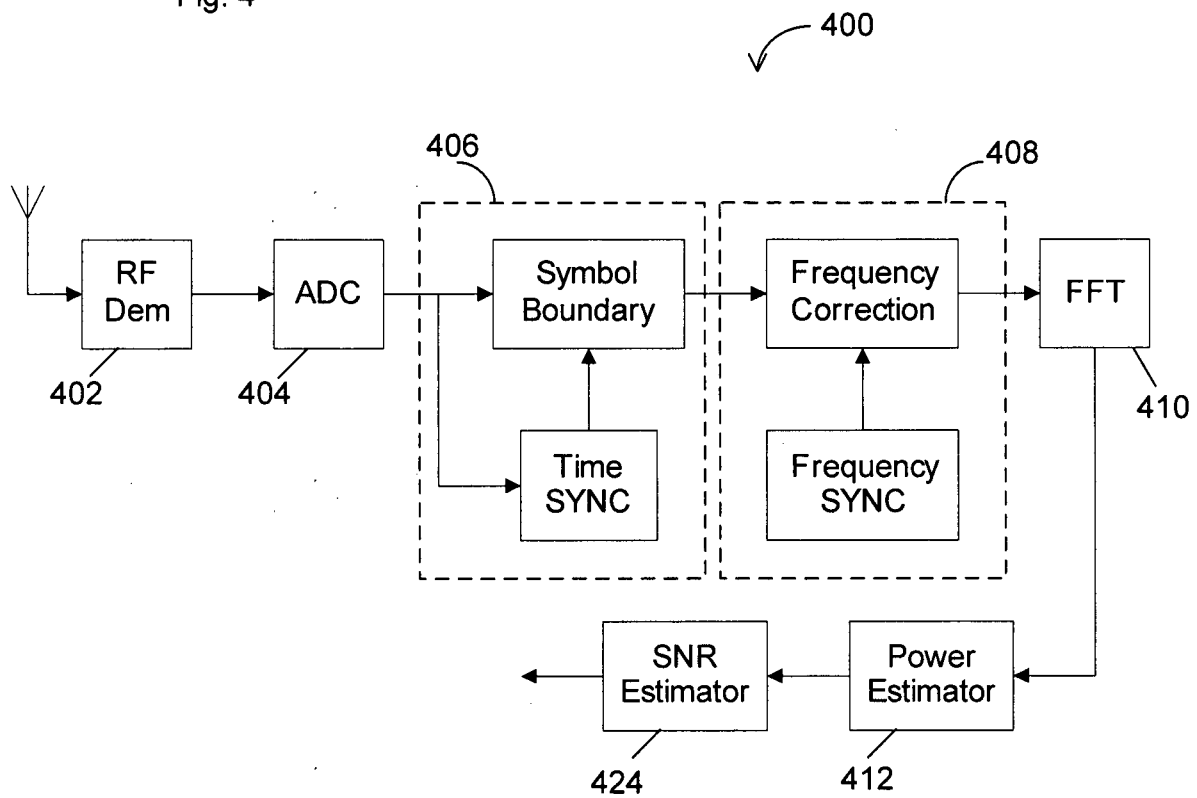
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Fig. 3... cont'd



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Fig. 4



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cont/d...

Fig. 5

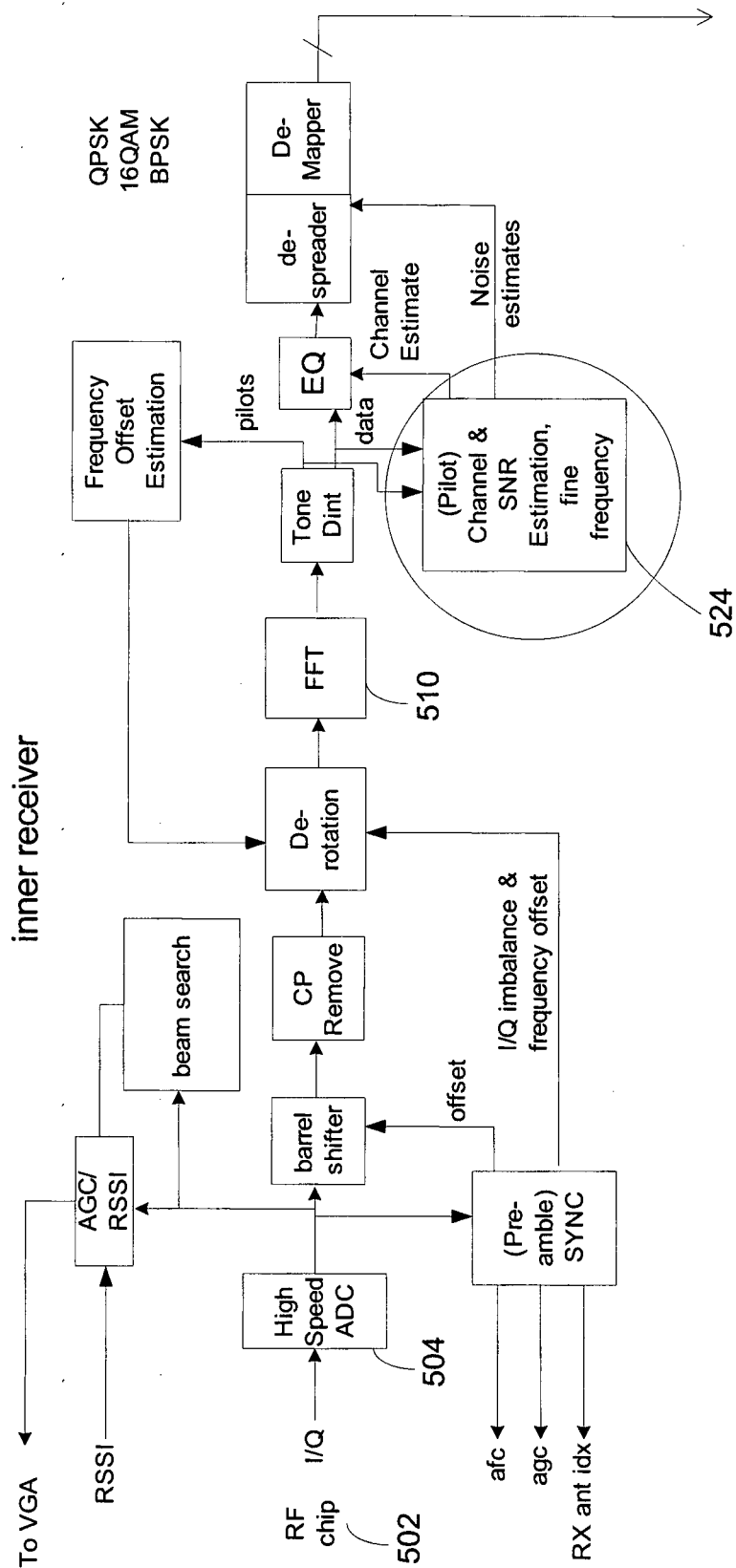
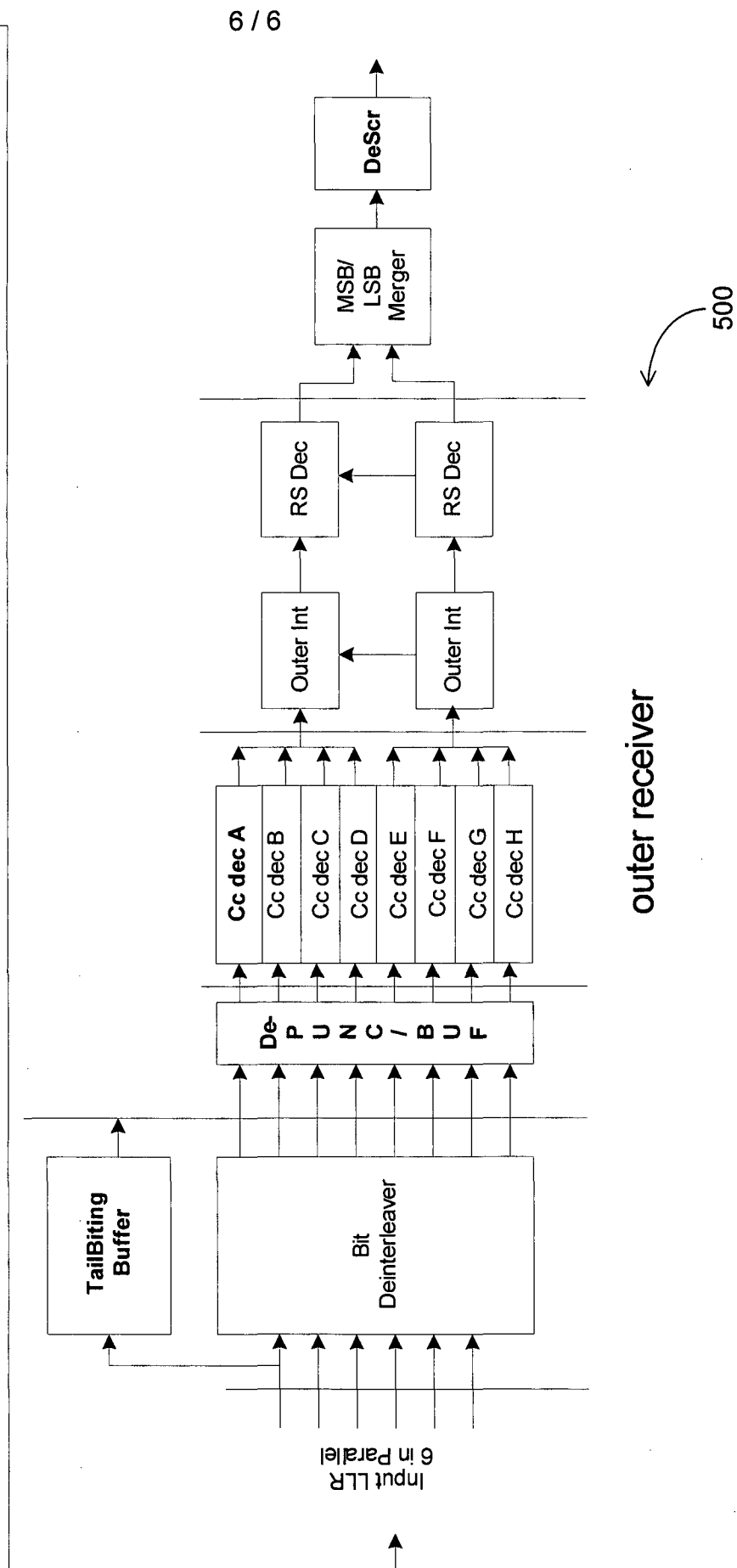


Fig. 5...cont'd



## INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU201 1/000047

## A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

**H04B 1/10** (2006.01)**H04L 27/26** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

## B : FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPODOC, WPI and INSPEC searched for keywords: SNR, OFDM, estimate, power ratio, average, noise and similar such words.

GOOGLE Scholar and the Internet searched for similar keywords as above plus additional words like sub-carrier, blind SNR, NNR, analogue to digital etc.

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2008/066338 A1 (XRONET CORPORATION) 05 June 2008 See whole document	1 - 11
A	US 7570722 B1 (LEE et al.) 04 August 2009 See whole document	1 - 11
A	XU, H. et al., "A novel SNR estimation algorithm for OFDM," <i>Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st</i> , vol.5, no., pp. 3068- 3071 Vol. 5, 30 May - 1 June 2005 See whole document	1 - 11

☐ Further documents are listed in the continuation of Box C
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Date of the actual completion of the international search 14 April 2011	Date of mailing of the international search report <b>19 APR 2011</b>
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustalia.gov.au Facsimile No: +61 2 6283 7999	Authorized officer <b>SHREYAS KUMAR</b> AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6222 3674



**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No.

**PCT/AU201 1/000047**

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member	
WO	2008/06633 8	US	201 0/00543 19
US	7570722	US	7756003
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			
END OF ANNEX			