



AUTOMATIC GAIN CONTROL SYSTEM AND METHOD

FIELD OF THE INVENTION

The present invention relates to an automatic gain control system and a method for automatically controlling gain, for example in a receiver system.

BACKGROUND OF THE INVENTION

Automatic gain control (AGC) is an essential element in modern communication receivers enabling the estimation of signal strength and the automatic adjustment of the amplification gain in order to maintain a relatively constant signal level. In typical conventional systems, such as in burst-mode wireless communication systems, for example, the Bluetooth system, the received signal needs to be level-adjusted prior to further processing. Furthermore, it is desirable to have a signal with a relatively constant strength (amplitude) to enable the full range of the processing circuits to be used. Moreover, the correct operation of analogue-to-digital converters can only be achieved if the excursion of the input signal is within the converter-specific dynamic range, thus avoiding saturation.

Automatic gain control circuits monitor the strength of the signal applied to the subsequent processing circuits, for example, an analogue-to-digital converter. A feedback signal is generated to readjust the gain of the amplifiers in the receiver stages, in a self-adaptive manner.

Conventionally, the feedback signal is typically generated by analogue circuitry. In systems where the signal is applied to an analogue-to-digital converter, if the level of the signal being applied to the analogue-to-digital converter exceeds the dynamic range of the analogue-to-digital converter, the control loop will have difficulty in reaching a steady state. This problem is particularly evident in applications where the received signal consists of



packets of data with a short header code (preamble) during which time the automatic gain control circuitry needs to settle.

In the Bluetooth system, the short (4-bit) preamble allows only a very short settling time (4 microseconds) for the automatic gain control circuitry to settle prior to processing of the data packet. Traditional automatic gain control circuits in most modern receivers have difficulty achieving precise gain adjustment of the received signal to a desired level within such a short response time.

Thus, there is a need for an improved automatic gain control system and method having a faster response time than that available in conventional systems.

Summary of the Invention

The invention is defined in the independent claims. Some optional features of the invention are defined in the dependent claims. By monitoring the amplitude of the signal from the variable gain control components and performing an adjustment, the time required to place the amplitude of any signal within a much smaller window which is close to a reference level is reduced. Subsequently, fine gain adjustment may be performed. As a result, the time required to bring the input to the analogue-to-digital converter out of saturation is significantly reduced.

The systems and methods described herein are intended primarily for the application to burst first mode communication systems, however they may also be easily implemented in a fully digital circuitry.

Brief Description of the Drawings

Preferred embodiments of the invention will now be described by way of example and with reference to the accompanying drawings in which:

Figure 1 is a schematic block diagram of an automatic gain control system according to a preferred embodiment;

Figure 2 is a flow chart of the operation of a sensor for use in the system of Figure 1 when comparing a signal amplitude with a reference level; and

Figure 3 is a flow chart of the operation of an automatic gain control system according to a preferred embodiment.

Detailed Description of Preferred Embodiments

Figure 1 shows a block diagram of an automatic gain control system 1 according to a preferred embodiment of the invention. The automatic gain control system 1 comprises four variable gain control components G1, G2, G3 and G4, four sensors s1, s2, s3 and s4, a digital control logic unit 2, an analogue-to-digital converter 4, and a digital-to-analogue converter 6.

The four variable gain control components G1 to G4 are cascaded so that they are connected in series. The output of the variable gain control component G1 is taken to the input of the sensor s1, the output of the variable gain control component G2 is taken to the input of the sensor s2 and the output of the variable gain control component G3 is taken to the input of the sensor s3. The output of the variable gain control component G4 is connected to the input of the analogue-to-digital converter 4. The output of the analogue-to-digital converter 4 is connected to the sensor s4, to further processing circuitry (not shown) and, together with the outputs c1-c4 from the sensors s1 to s4, to the input of the digital control logic unit 2. The sensor s4 may alternatively be an analogue sensor connected to the output of G4.

The output of the digital control logic unit 2 is connected to the input of the digital-to-analogue converter 6. The outputs of the digital-to-analogue converter 6 are connected to the control inputs of the variable gain control components G1 to G4. The digital-to-analogue converter 6 provides control

signals g_1 to g_4 to the variable gain control components G_1 to G_4 respectively.

The automatic gain control system 1, as shown in Figure 1, generates a plurality of feedback signals to control the gain of the variable gain control components G_1 to G_4 based on the output of the analogue-to-digital converter 4 and the outputs c_1 to c_4 of the sensors s_1 to s_4 .

The purpose of the automatic gain control system 1 is to adjust the scaling of the signal level applied to the analogue-to-digital converter 4 to ensure the full dynamic range of the analogue-to-digital converter 4 is used.

Sensor s_1 monitors the amplitude of the signal at the output of the variable gain control component G_1 in order to determine whether it is greater or smaller than the reference level V_{ref1} . As shown in Figure 1, if the output of G_1 is greater than V_{ref1} , $c_1 = 1$ is generated at the output of the sensor s_1 . If the output of the variable gain control component G_1 is less than V_{ref1} , $c_1 = 0$ is generated at the output of the sensor s_1 . The output c_1 from the sensor s_1 , is applied to an input to the digital control logic unit 2.

Each of the sensors s_1 to s_4 illustrated in Figure 1 performs an identical function, so the above description of the operation of sensor s_1 is applicable to the other sensors s_2 to s_4 . The respective outputs of the variable gain control components G_2 to G_4 are compared with the corresponding reference levels V_{ref2} to V_{ref4} respectively and the output signals c_2 to c_4 of the sensors s_2 to s_4 are generated respectively.

The choice of reference levels V_{ref1} to V_{ref4} used by the sensors s_1 to s_4 is dependent upon the application of the system in which the automatic gain control circuit 1 is to be used.

The main function of sensors s_1 to s_4 is to compare the signal amplitude with a reference level. Implementation can therefore be greatly simplified when

the sensors s1 to s4 are fabricated in fully digital circuitry where an analogue filter is not required.

An illustrative example of the operation of a digital implementation of the sensors shown in Figure 1 is shown in Figure 2.

The incoming signal, which may be comprised of an in-phase component I and a quadrature component Q , has an amplitude $\sqrt{I^2 + Q^2}$. As it is difficult to determine the amplitude $\sqrt{I^2 + Q^2}$, the in-phase and quadrature components are treated separately. The absolute values ($\text{abs}(I)$ and $\text{abs}(Q)$) of the in-phase I and quadrature Q components are used. The absolute values of the in-phase I and quadrature Q components of the incoming signal are not a constant and they may sometimes be greater than the reference level and sometimes smaller than the reference level. However, the amplitude $\sqrt{I^2 + Q^2}$ of the signal should be a constant.

To compare the amplitude (V) of the input signal to the sensor s1 with the predetermined reference level V_{ref} , it is not generally sufficient to determine that the amplitude is greater than the reference level by observing only one sample of the signal, as this may be caused by noise, or the sample may be the maximum value of the signal. Two decision rules (case 1 and case 2) are proposed, therefore, to determine whether the amplitude of the signal is greater than or less than the reference level, with the two alternative rules (case 1 and case 2) being treated independently, as shown in Figure 2 which illustrates the operation of a sensor for use in the automatic gain control system of Figure 1 according to an embodiment of the invention.

In a first stage 10, as shown in Figure 2, at the start of the cycle, the internal variables flag 1 and flag 2, and the time t as measured by a time counter are set to 0. Flag 1 and flag 2 are two-state variables which indicate whether or

not the signal amplitude is greater than a reference level V_{ref} based on the decision rules case 1 and case 2, respectively.

After the internal variables have been set to 0 in the first stage 10, in a second stage 12 a determination is made as to whether or not the absolute value of either of the in-phase or quadrature components is greater than a reference value, (that is, if either $\text{abs}(I) > V_{ref}$ or $\text{abs}(Q) > V_{ref}$). If either of the in-phase or quadrature components is greater than a reference value, then internal variable $\text{Clip}(n)$ becomes equal to 1. $\text{Clip}(n)$ is a two-state variable which indicates whether or not the signal amplitude at an n th time instant is greater than a reference level V_{ref} .

If the absolute value of neither of the in-phase or quadrature components is greater than a reference value, (that is, if both $\text{abs}(I) < V_{ref}$ and $\text{abs}(Q) < V_{ref}$), the internal variable $\text{Clip}(n)$ is 0.

If $\text{Clip}(n)$ is greater than $\text{Clip}(n-1)$, then the two-state internal variable $\text{rise}(n)$ is set so that $\text{rise}(n)=1$. $\text{Rise}(n)=1$ indicates that $\text{clip}(n)$ has changed state from 0 to 1 since the previous sample of the incoming signal. This indicates that an increase in the signal amplitude across the reference level V_{ref} has occurred.

However, if $\text{Clip}(n)$ is less than or equal to $\text{Clip}(n-1)$, then $\text{rise}(n)=0$.

In the second stage 12, the incoming signal is examined according to both case rules 1 and 2.

Case 1

This rule is applied to the incoming signal as follows. The incoming signal is sampled at intervals t_i for a period T_0 , during which time every sample of the incoming signal V (that is $\text{abs}(I)$ and $\text{abs}(Q)$) is compared with V_{ref} . If $\text{rise}(n)$ is again recorded as being 1 during the period T_0 , then flag 1 is set to

1 (that is to TRUE) for a period T_2 . If $\text{rise}(n)=1$ is not detected during the period T_2 , then flag 1 is reset to 0 after time T_2 .

However, if during the period T_2 , $\text{rise}(n)$ is detected as being 1, then flag 1 is maintained at flag 1=1 for a further period T_2 from this instant.

Similarly, if a further instance of $\text{rise}(n)=1$ occurs during the period T_2 , flag 1 will be extended by an additional period T_2 from this instant, on each occasion.

Case 2

This rule is also applied to the incoming signal in the second stage 12. Initially, the incoming signal V is compared with V_{ref} at intervals t_i for a period T_1 . If every sample of V is greater than or equal to V_{ref} during the period T_1 , that is $\text{Clip}(n)=1$, flag 2 is set to 1 for a period T_2 .

If, within the period T_2 , the sampled incoming signal V is greater than V_{ref} , that is $\text{Clip}(n)=1$, then the sampling period is extended by a further period T_2 from that instant and the signal is continuously sampled in this extended period.

If, within the period T_2 , a sample of the incoming signal V is not greater than V_{ref} , that is $\text{Clip}(n)=0$, then flag 2 is reset to 0 at a time T_2 from this instant.

As shown in Figure 2, the two cases 1 and 2 are treated independently but preferably simultaneously.

For both cases, the samples are counted in the time counter (not shown) and the periods T_0 to T_2 are determined by the time counter.

For each sample of the incoming signal, flag 1 is examined in a third stage 14 to determine its state.

If flag 1 equals 1, in a fourth stage 16, a determination is made as to whether or not $\text{rise}(n)$ equals 1. If $\text{rise}(n)$ equals 1, then t is reset to 0 in a fifth stage 18 to restart the period $T2$. However, if $\text{rise}(n)$ equals 0, and $T2$ has expired, then flag 1 is set to 0 in a sixth stage 20 and t is reset to 0.

If, in the third stage 14, it is determined that flag 1 =0, and $\text{rise}(n)=1$ for a second time during the period $T0$, then, in a further stage 22, flag 1 is set to 1 and t is set to 0.

As shown in Figure 2 with regard to case 2, in an alternative third stage 24, a determination is made as to whether or not the variable flag 2 equals 1. If flag 2 equals 1, in an alternative fourth stage 26, a determination is made as to whether or not $\text{Clip}(n)$ equals 1. If $\text{Clip}(n)$ equals 1, then t is reset to 0 in a further stage 28 to maintain flag 2 equal to 1 for a period $T2$ from this instant.

However, if $\text{Clip}(n)$ equals 0, and $T2$ has expired, then flag 2 is set to 0 in a further stage 30 and t is reset to 0.

If, in the alternative third stage 24, it is determined that flag 2 equals 0 and if $\text{Clip}(n)$ has been equal to 1 for the period $T1$, then in a further stage 32 flag 2 is set to 1 and the time t is reset to 0.

In a final stage 34, if it is determined that flag 1 equals 1 or flag 2 equals 1, then this sets the output of the sensor illustrated in Figure 2 to 1 and the time counter is incremented so that $t=t+1$. The output of the sensors is denoted as $c(n)$. For example, for sensor s_1 , the output variable is defined

as c_1 in Figure 1, which is an input variable to the Digital Control Logic Unit 2 of the system of Figure 1.

The above procedure is then repeated for the next sample.

However, if neither flag 1 nor flag 2 equals 1, the output of this sensor is set to 0 and the time counter is reset so that t equals 0.

T_0 , T_1 and T_2 are positive constants which are determined according to the application.

The operation of the digital control logic unit 2 is illustrated by the flow chart shown in Figure 3. The digital control logic unit 2 controls the variable gain control components G_1 to G_4 in response to the outputs c_1 to c_4 of the sensors s_1 to s_4 and the sample of the analogue-to-digital converter 4 output. The control exerted by the digital control logic unit 2 is in two stages, namely, coarse gain control and fine gain control.

Figure 3 shows the procedure of the automatic gain control operation as comprising the following steps:

1. At a starting time, in a first step 36 the gain of the variable gain control components G_1 to G_4 is set to a non-zero intermediate value. The advantage of a non-zero setting is that when the received signal is very weak, the automatic gain control system can reach the steady state more quickly than automatic gain control systems initialised with a zero value.
2. In a second step 38, the amplitudes of the outputs c_1 to c_4 of the sensors s_1 to s_4 are sensed. The sensors s_1 to s_4 compare the amplitude of the output of the variable gain control components G_1 to G_4 with the predefined reference level V_{ref} .

3. In a third step 40, a determination is made as to whether or not any of the outputs from sensors s1 to s4 are TRUE, that is whether any of c1 to c4 equals 1. If none of the outputs from sensors s1 to s4 is "TRUE" and a coarse gain adjustment has been made within the first time duration T3, then no fine gain adjustment will be made. If none of the outputs from sensors s1 to s4 is "TRUE" and there is no coarse gain adjustment within the pass time duration T3, a fine gain adjustment is performed in a fourth step 42 in response to the samples collected at the analogue-to-digital converter 4 output, according to the following equation:

$$g_n = g_{n-1} + (\log_{10} V_{ref} - \log_{10} \text{abs}(v_{on}))b \quad \dots(1)$$

where:

g_n is the adjusted gain, that is, the gain at time instant n

g_{n-1} is the gain at time instant n-1

v_{on} is the output of the analogue-to-digital converter 4 at time instant n

$\text{abs}(v_{on})$ is the absolute value of the output from the analogue-to-digital converter 4 at time instant n;

V_{ref} is the reference amplitude; and

b is a constant.

The most recent gain of each gain control component G1 to G4 is updated based on the latest value of g_n .

The operation given by equation (1) is an example only. Other known prior art operations may be applied to the present invention.

After the fine gain adjustment has been performed, the outputs c1 to c4 of the sensors s1 to s4 are resampled and the process repeated.

4. If any output of the sensors s_1 to s_4 is "TRUE" a determination is made in a further step 44 as to whether or not a coarse gain adjustment has been detected within the past time duration T_3 . If no coarse gain adjustment has been detected, a coarse gain adjustment is performed in a further step 46. After the coarse gain adjustment has been performed, the outputs c_1 to c_4 of the sensors s_1 to s_4 are resampled and the process repeated.

If a coarse gain adjustment has been detected in the further stage 44, then no gain adjustment is made and the outputs c_1 to c_4 of the sensors s_1 to s_4 are resampled and the process repeated. The rules of operation of a coarse gain adjustment are illustrated in the example given below:

- (a) if $c_1 = 1$, the gain of G_2 - G_4 is set to 0dB ($g_{2-4} = 0$), the gain g_1 of G_1 is reduced by 6 dB ($g_1 = g_1 - 6$)
- (b) if $c_2 = 1$, the gain of G_3 - G_4 is set to 0dB ($g_{3-4} = 0$), the gain of G_2 is reduced by 6dB ($g_2 = g_2 - 6$)
- (c) if $c_3 = 1$, the gain of G_4 is set to 0dB ($g_4 = 0$), the gain of G_3 is reduced by 6dB ($g_3 = g_3 - 6$)
- (d) if $c_4 = 1$, the gain of G_4 is reduced by 6dB ($g_4 = g_4 - 6$).

By monitoring the amplitude of the signal from the variable gain control components G_1 to G_4 and performing the coarse gain adjustment, the time required to place the amplitude of any signal within a much smaller window which is close to the reference level V_{ref} is reduced. Subsequently, the fine gain adjustment may be performed. As a result, the time required to bring the input to the analogue-to-digital converter 4 out of saturation is significantly reduced.

The digital-to-analogue converter 6 is then used to generate the control signals to the variable gain control components G1 to G4.

In summary, preferred embodiments of the automatic gain control system and method for implementing the automatic gain control system of the present invention are considerably advantageous over known techniques. For example, embodiments of the present invention may be implemented with fully integrated digital circuitry and simple, robust and inexpensive sensors may be used. Also, one or more preferred embodiments of the invention permit a faster settling time for the automatic gain control based on the monitoring of the amplitude of the received signal than is possible in conventional systems.

It will be appreciated that the scope of the present invention is not restricted to the described embodiments. For example, whilst the embodiments have been described in terms of four sensors and four variable gain control components, a different number of such components may be used. Numerous other modifications, changes, variations, substitutions and equivalents will therefore occur to those skilled in the art without departing from the spirit and scope of the present invention.

Claims:

1. An automatic gain control system comprising:

5 a plurality of variable gain stages, each variable gain stage having an output, a signal input and a control input, said plurality of variable gain stages being connectable in series;

10 a plurality of sensors, each sensor having an output and an input, the input of each sensor being connectable to a respective output of said plurality of variable gain stages;

15 an analogue-to-digital converter having an output and an input, the input of the analogue-to-digital converter being connectable to the output of a final one of said plurality of variable gain stages;

20 a control unit having an output and an input, the input of the control unit being connectable to the outputs of the sensors and to the output of the analogue-to-digital converter; and

25 a digital-to-analogue converter having an input connectable to the output of the control unit, the digital-to-analogue converter further having a plurality of outputs, the control inputs of each of the plurality of variable gain stages being connectable to an output of the digital-to-analogue converter, the outputs of the digital-to-analogue converter controlling the gain of the plurality of variable gain stages.

2. The automatic gain control system of claim 1, comprising N variable gain stages and N sensors, where N is an integer of two or more.

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3. The automatic gain control system of claim 1, wherein said plurality of sensors are arranged to determine if the output from the plurality of variable gain stages is greater than a predetermined reference level.

4. The automatic gain control system of claim 1, wherein said plurality of sensors are arranged such that the output of at least one of the plurality of sensors is set if the output from the plurality of variable gain stages is greater than a predetermined reference level.

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5. The automatic gain control system of claim 1, wherein said control unit is a digital control logic unit.

6. The automatic gain control system of claim 1, wherein each of said variable gain stages has a gain associated therewith, said control unit being arranged to control the gain of each of said plurality of variable gain stages.

7. The automatic gain control system of claim 6, wherein said control unit is arranged to control the gain of each of said plurality of variable gain stages using at least one of: coarse gain control, and fine gain control.

8. A burst-mode wireless communication system comprising the automatic gain control system according to claim 1.

9. A method for automatically controlling gain in a receiver system comprising:

amplifying an incoming signal using a plurality of variable gain stages connected in series, the plurality of variable gain stages each having an output signal and a gain;

comparing the output signal of each of the variable gain stages with a reference level using a plurality of sensors to determine if the output signal is greater than or less than the reference level, each of said plurality of sensors having an output;

if the output signal is greater than the reference level, setting the output of at least one of the plurality of sensors;

5 passing the output signal from one of the plurality of variable gain stages to an analogue-to-digital converter to digitise the output signal to form a digitised signal;

10 passing the digitised signal together with the output from at least one of the plurality of sensors into a control logic unit to produce a digital signal; and

converting said digital signal to a plurality of analogue signals to control the gain of the plurality of variable gain stages.

15 10. The method of claim 9, further comprising setting initially the gain of at least one of the plurality of variable gain control stages to a non-zero value.

20 11. The method of claim 9, further comprising setting initially the gain of each of the plurality of variable gain control stages to a non-zero value.

25 12. The method of claim 9, further comprising sampling the incoming signal at regular intervals for a first predetermined time period, and extending the first predetermined time period for a second predetermined time period if the incoming signal is greater than the reference level within the first predetermined time period.

30 13. The method of claim 12, further comprising restarting the second predetermined time period if during said second predetermined time period the incoming signal being sampled exceeds the reference level.

14. The method of claim 12, further comprising producing a signal to be passed to the input of the control unit when the output of one or more of the one

or more sensors indicates that the incoming signal being sampled exceeds the reference level during the first predetermined time period.

15. The method of claim 12, wherein if after sampling the input signals the
5 output of any of the sensors is set, the method further comprises:

10 reducing by a predetermined amount the gain of the variable gain stage corresponding to the sensor whose output has been set using said control logic unit, said predetermined amount corresponding to a coarse gain jump;

setting to around zero dB the gain of the variable gain stages subsequent to the variable gain stage whose gain has been reduced; and resampling said incoming signal.

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16. The method of claim 15, wherein the step of reducing the gain of the variable gain stage comprises reducing the gain by around 6dB.

17. The method of claim 12, further comprising making a fine adjustment to
20 the gain of one or more of the variable gain stages if none of the outputs of the one or more sensors is set, said fine adjustment being determined from the digitised signal output from the analogue-to-digital converter.

18. The method of claim 17, wherein the step of making a fine gain adjustment
25 comprises adjusting the gain of at least one of the variable gain stages according to the equation:

$$g_n = g_{n-1} + (\log_{10} V_{\text{ref}} - \log_{10} \text{abs}(v_{on}))b$$

where g_n is the adjusted gain at time instant n , g_{n-1} is the gain at time instant $n-1$, $\text{abs}(v_{on})$ is the absolute value of the output from the analogue-to-digital
30 converter at time instant n , V_{ref} is the reference amplitude, and b is a constant.