Automatic Transmit Power Control of a Digital Fixed Wireless Link with Co-Channel Interference

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Abstract— **In this paper, a study is presented of the dynamic behavior of an automatic transmit power control (ATPC) loop in a single fixed wireless system (FWS) link subject to multipath fading and an uncorrelated co-channel interferer that does not use ATPC (this represents a so-called non-ATPC FWS link or a fixed satellite link). Fundamental questions include the sensitivity of an ATPC link to multipath interference and the co-channel interference that may be caused by a non-ATPC interferer. In the context of the present project, a good example of a non-ATPC interferer is a fixed satellite to which one antenna in a fixed microwave link has partial view. A computer model was developed that constitutes a useful tool in describing; simulating and analyzing an ATPC loop in a single FWS link. With the aid of this model, results are presented on the sensitivity of an ATPC loop in a FWS link with respect to channel conditions, non-ATPC interference and parameter settings.**

Index Terms—**Power Control, Fixed Wireless.**

I. Introduction

TRADITIONALLY, automatic transmit power control (ATPC) techniques have been utilized in microwave radio links in order to combat rain fading (attenuation). This is also sometimes referred to as *power diversity*. Initially, the link is designed such that the transmitter power is sufficiently large to achieve a given quality of service goal, such as bit error rate, under clear sky conditions. When the link experiences an attenuation due to rain, the transmit power is increased gradually and up to the maximum transmission power limit set by a government authority. The particular technique used in increasing or decreasing power at the transmitter, and the method of estimating power at the receiver, can be used to differentiate ATPC techniques or algorithms. To illustrate [27] the fundamental ideas behind the use of ATPC techniques in fixed wireless systems, consider the case of two FWS links. Under non-rainy conditions, each link has a nominal transmitted power that is required in order to achieve a given quality. This quality measure can be for example the bit error rate (BER). Suppose now that link A is subject to rain fading while at the same time link B remains under clear-sky conditions. The presence of an ATPC loop in link A will increase the transmitted power in order to overcome the drop in received power and subsequent loss of quality (for example, an increase in bit error rate value). This will work fine on link A. However, it is also possible that link B will receive some of the power sent by the transmitters in link A and therefore will suffer co-channel interference (CCI). The introduction of a different (uncorrelated) signal power in link B will give as a result a loss of link quality (as another example, this could be an increased outage time).

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A. *The use of ATPC techniques in wireless networks*

In recent years, the use of ATPC techniques to increase the reliability and efficiency of wireless networks and fixed microwave links has increased substantially. In 2001, the Federal Communications Commission (FCC) approved the use of ATPC in Broadcast Auxiliary Services operating in the 2 GHz, 7 GHz and 13 GHz bands [3]. Since 1996 when the Commission amended its Part 101 rules, ATPC has been used successfully in the FS microwave bands. With respect to the maximum transmit power limit, the FCC rules in part 74.535, for the 2 GHz, 6.4 GHz, 7GHz, 13 GHz and 18 GHz bands, that "The EIRP of transmitters that use Automatic Transmitter Power Control (ATPC) shall not exceed the EIRP specified on the station authorization. The EIRP of non-ATPC transmitters shall be maintained as near as practicable to the EIRP specified on the station authorization." [4].

In a 2003 report [5], it is stated that ATPC allows transmitters to operate with a certain "nominal power" during normal propagation conditions. If the receiver detects a drop in received signal level, the transmit power is incrementally or instantaneously increased to the maximum allowable power level, depending on the manufacturer's design. Radios equipped with ATPC have the following advantages over their non-ATPC equipped counterparts:

1) Simplified frequency coordination in congested areas
2) Less power consumption
3) Increased MTBF (Mean time between failures)

The application of ATPC techniques in fixed wireless links operating in the 70/80 GHz bands is presented in [7]. Most recently, in the U.S.A., the Advanced Television Systems Committee (ATSC) has proposed a new standard that incorporates the use of ATPC techniques [8]. No details are given however on exactly how the ATPC technique is to be implemented, but rather a provision of a feedback link with a measure of the received power made available to the transmitter. To further illustrate other applications of ATPC technology we note that, in the 2 GHz band, Wireless Communications Association International, Inc. (TIA) submitted a document to the FCC in which ATPC plays a central role [9].

Considerations of ATPC technology applications in fixed wireless networks, such as WiMax, appear in the IEEE 802.16 standard subgroup in charge of point-to-multipoint links [11]. The IEEE standard for WiMax [16] states, in section 8.1.11.2, on the subject of SS-to-BS interference that: “In PMP systems, SS-to-BS interference may be evaluated by use of a simulation program. It is clear that an interfering SS could be relatively close to a victim BS, but the level of interference depends on the relative locations of the BSs of the two systems (which affects the antenna pointing direction), on the use of automatic transmit power control (ATPC), and on possible differential rain fading.

Another potential advantage of ATPC technology is in LMDS systems, where it is claimed that, with power control, the carrier-to-interference (C/I) ratio can be improved by at least 2 dB [12]. ATPC techniques also find applications in interference cancellation between satellite and terrestrial systems in the 28 GHz band. To minimize the carrier power, automatic transmitter power control (ATPC) is employed at the ground terminals, and also at the satellites in some proposed NGSO systems. When fading events occur (for example, under rain conditions) transmitter power is increased to compensate for the additional loss. The use of ATPC minimizes power consumption under clear-sky conditions and therefore eases the problem of sharing spectrum with other networks by reducing the potential interference.

A study [13] uses an ATPC range equal to 10 dB. In the 43 GHz band [14], ATPC provides a transmission power range from -30 dBW down to -50 dBW. The use and limitations of ATPC techniques, in point-to-point wireless systems over higher frequency bands, is also discussed by the FCC[18]. Moreover, on the topic of earth stations in satellite systems, the following was ruled by the RABC Fixed Wireless Communications Committee[24]:

The European Union has also issued recommendations on the use of ATPC in fixed-satellite services [25]: “that the use of transmit power reduction mechanisms (e.g. Automatic Power Control and/or Power Setting) by the FWA terminal stations will ensure that the maximum EIRP density level defined in considering m) will not be exceeded by a single station towards the GSO arc;” and “that FSS systems using uncoordinated FSS earth stations in the bands referred to in Decide 1 and 2 shall implement Automatic Power Control in the uncoordinated FSS earth stations and/or automatic on-board satellite gain control;” Also in Europe, ATPC techniques have been integrated into so-called “Technical Frequency Assignment Criteria for Lower 6 and Upper 6 GHz Bands” [15].

To date, the best study on the validity of ATPC techniques in fixed digital wireless systems is that produced by the Ofcom group in the UK [26]. In particular, the study concludes that: “The potential advantages of ATPC reported in the literature include (i) Reduced average power consumption; (ii) extended equipment mean time between fades (MTBF); (iii) Elimination of the ‘upfade’ problem in receivers; (iv) Improved outage performance due to the reduced influence of adjacent channel interference (ACI); and (v) easier frequency co-ordination in areas of high radio-relay station density.”

TABLE I
PARAMETERS OF THE COMPUTER MODEL OF AN FWS LINK

Parameter	Value
Symbol rate, R	24 Mbaud
Pulse shape	Square-root raised-cosine
Roll-off factor, a	0.25
Bandwidth, B	30 MHz
Multipath model	Rummler
Path delay, t=1/6B	5.56 ns
Modulation	64-QAM
Equalizer type	Adaptive Linear (FF) with LMS algorithm
Equalizer taps	15
Equalizer step	$7.5x10^{-4}$

II. MODEL OF AN ATPC FIXED WIRELESS LINK

A. System model

A computer model was developed to facilitate the study of the performance of ATPC techniques in an FWS link with respect to rain attenuation, co-channel interference (CCI), and loop parameter settings. In its current form, this model applies to a 30 MHz bandwidth frequency band and it is implemented in the complex baseband domain. (This is done for the purposes of shortening the simulation time. It should be noted that a full RF (bandpass) model could be easily implemented. However, the simulation time would be too large.) The model has been implemented using Matlab™ software with the Simulink™ tool and the Communications and Signal Processing Blocksets. The main model parameters are summarized in Table I. Importantly, we note that the model assumes an ideal return channel without noise over which the required transmitter gain factor is conveyed. The rain attenuation factor G is a gain that is computed from the rain attenuation A (in dB) as follows:

$$G = 10^{-A/20} \quad (1)$$

The transmission gain factor G_{Tx} at the transmitter is

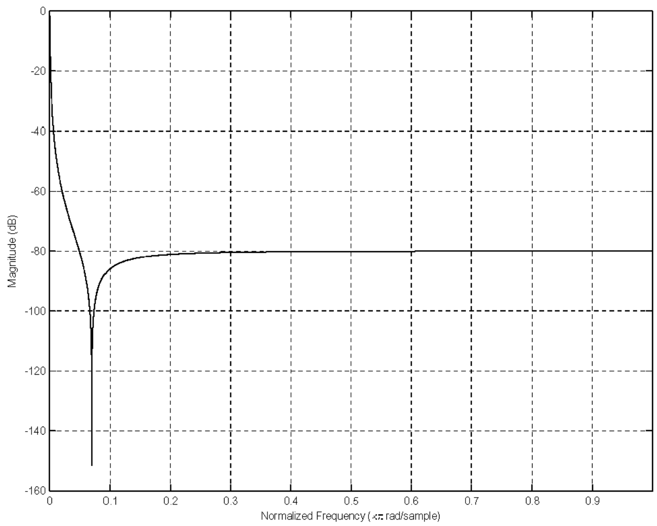

Fig. 1. Magnitude spectrum of a narrowband lowpass filter (LPF), used in estimation of the received power

initially set equal to 1 (this corresponds to a value of 0 dB in power increase) and is modified periodically by the ATPC control loop, based on the average received power, as explained below. Thus an important parameter of an ATPC technique or algorithm is the rate at which the loop operates. This issue is addressed in a later section.

B. Multipath channel model

The multipath channel model used in this study is the standard three-path channel model proposed by Rummler [29]. The path delay t is computed using the so-called factor-of-six rule [30], [31], $\tau = 1/6 f_B$, where $f_B = (1+\alpha)R$ is the channel bandwidth and α=0.25 is the roll-off factor of the square-root raised-cosine filters used at the transmitter and receiver.

III. Proposed ATPC algorithm

A. Power measurement

The metric used to drive the ATPC loop is the received power. It is therefore very important to obtain a reliable and accurate estimate of the received power. In the SJSU model, the received power is estimated in the digital baseband domain as follows. The matched filter outputs are sampled at symbol rate, and the square magnitudes computed. These numbers are then passed through a digital 2nd order Chebyshev type-II IIR narrow lowpass filter (LPF). This filter was designed using the Filter Design and Analysis (FDA) tool in Matlab™ and was specified to have a normalized stopband frequency equal to 0.05 with an attenuation value of 80 dB. Fig. 1 shows a plot of the magnitude spectrum of the filter.

B. Algorithm

An ATPC algorithm is hereby defined as a method of computing a transmitter gain factor GT required at the transmitter end of a link in order to reach a desired average power at the receiver end. For example, an ATPC algorithm was been applied to cellular systems in [32]. In the SJSU model, and only for convenience, the target average power has been set to unity. This can be easily changed to other values if desired.

The average received power is available at the output of a digital narrowband lowpass filter, as explained above. Let PR[n] denote the estimated average received power. Based on the value PR[n], the ATPC algorithm computes a power step

$$\Delta P = g\left(1 - P_R[n]^{-1}\right), \qquad (2)$$

where g() denotes a nonlinear function which is essentially the combination of a dead zone and a two-level quantizer.

The parameters of this nonlinear function depend on pre-specified power steps that are used to increase or decrease power at the transmitter. In this work, the increments in transmitted power are set to standard values of dB. These values are found to be standard in many commercial ATPC products in the market. The ATPC algorithm then proceeds to compute the value of the new required transmitter power as follows:

$$P_T[n+1] = (1+\Delta P) P_T[n] \qquad (3)$$

This value needs to be saturated in order not to exceed the maximum allowable transmit power. In the ATPC model, the algorithm has a 30 dB range, with the minimum transmitted power set to 1 (0 dB) and the maximum transmitted power equal to 1000 (30 dB). Finally, the value of transmitter gain factor G_T is obtained as $G_T = \sqrt{P_T[n+1]}$.

C. ATPC loop

One of the contributions of the work reported here is in the analysis of the dynamics of the ATPC control loop. This is a problem similar to that of phase-locked loops (PLL) in the sense that feedback and nonlinear functions are involved. Thus of great interest is the dynamic behavior of the ATPC control loop with respect to various parameters such as rain attenuation level, ATPC step size and ATPC update interval.

IV. Results

A. Sensitivity to ATPC loop sampling rate

It is important that the ATPC control loop be updated slowly. This means that the sampling period of the loop needs to exceed the length of the impulse response of the digital averaging filter. Otherwise, an unstable situation will occur, as will be shown shortly, where both the transmitter gain factor G_T and the estimated average received power $P_R[n]$ oscillate

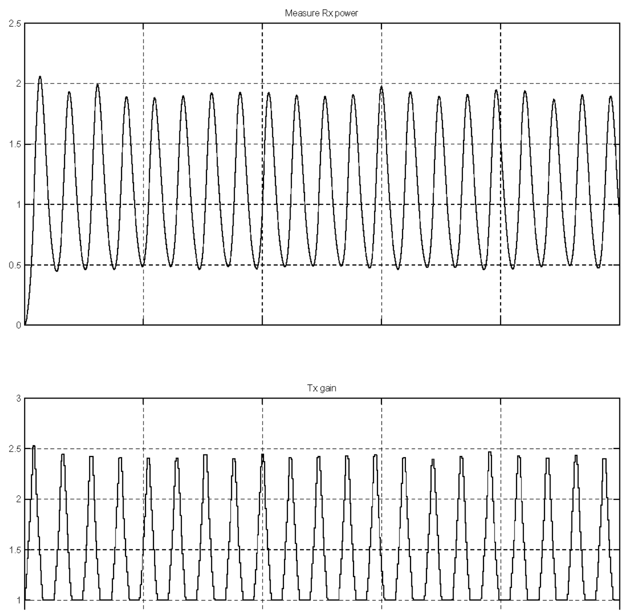

Fig. 2. Dynamic behavior of the average power and transmitter gain factor for DT/T = 100

around the desired (steady) values.

In the SJSU model, the ATPC loop is activated once every DT seconds, where DT is a multiple of the symbol period T, and can be set by the user.

To illustrate this point, the SJSU model was run using a normalized loop sampling interval equal to DT/T=100, and rain attenuation A = 3 dB. Clearly, the ATPC loop becomes unstable and oscillates, as shown in Fig. 2, around the desired values. Both the estimated average received power P[n] (shown on the top) and the transmitter gain factor GT (shown on the bottom) oscillate and as a result the link will eventually fail.

As Figures 3 to 5 show, increasing the value of the sampling period (i.e., decreasing the sampling rate) of the ATPC loop improves stability. In the results reported in these figures, the rain attenuation was set to A = 3 dB. We also see from these results that the value of the estimated average power remains within a value of 1 dB from the target value (0 dBW), just as expected. Using a normalized sampling period of DT/T = 200 results in an estimated mean received power approximately equal to 1 (the desired value). On the other hand, a value of DT/T = 500 results in a mean value greater than 1, and a value of DT/T = 1000 results in a mean value less than unity.

B. Sensitivity to rain attenuation

The model was used to analyze the effect of rain attenuation A (dB) on the performance of an ATPC loop using a fixed sampling factor DT/T =200. Rain attenuation values of A = 6 dB and A = 10 dB give the results shown in Figs. 6 and 7, respectively. These computer simulation results suggest that as the rain attenuation value increases, the ATPC loop might

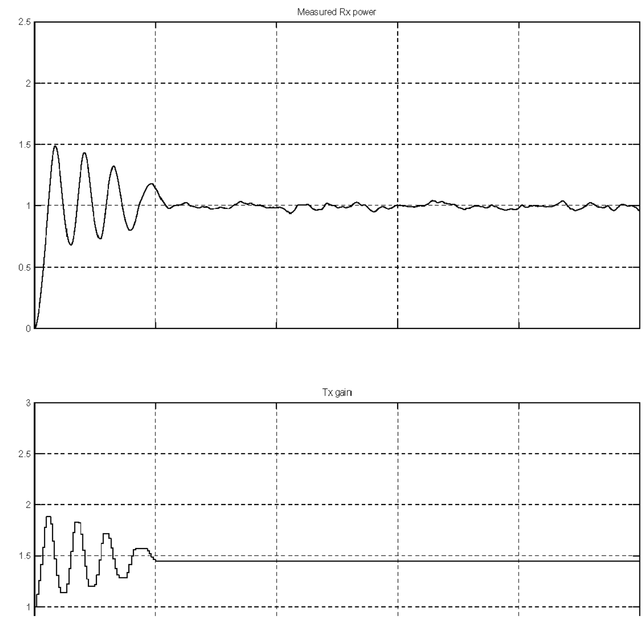

Fig. 3. Dynamic behavior of the average power and transmitter gain factor for DT/T = 200

become less stable

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C. Sensitivity to co-channel interference

We have also investigated the effect of co-channel interference (CCI) on the performance of an ATPC loop. To study this effect, we set the values DT/T = 1000, A = 6 dB, and the channel-to-interference ratio C/I (dB) to infinite (no interference), 0 dB (equal powers) and 6 dB. Simulation results are shown in Fig. 8. Based on these results, which apply to one link with one (uncorrelated) interferer, the effect of CCI

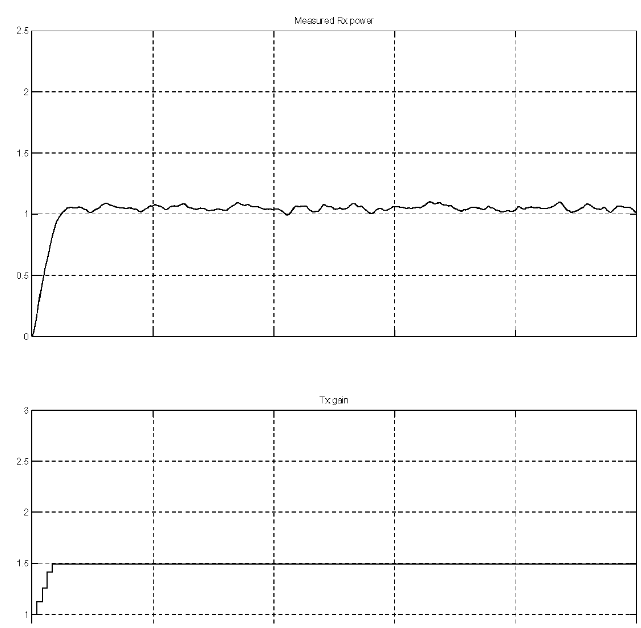


Fig. 4. Dynamic behavior of the average power and transmitter gain factor for DT/T = 500

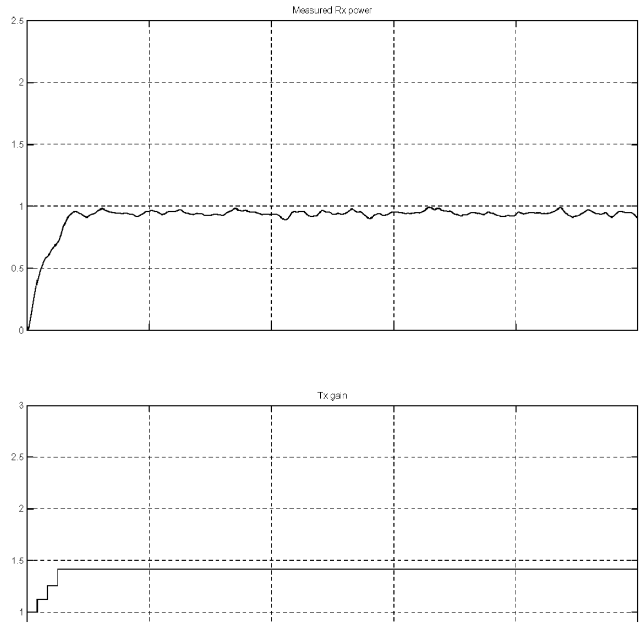


Fig. 5. Dynamic behavior of the average power and transmitter gain factor for DT/T = 1000

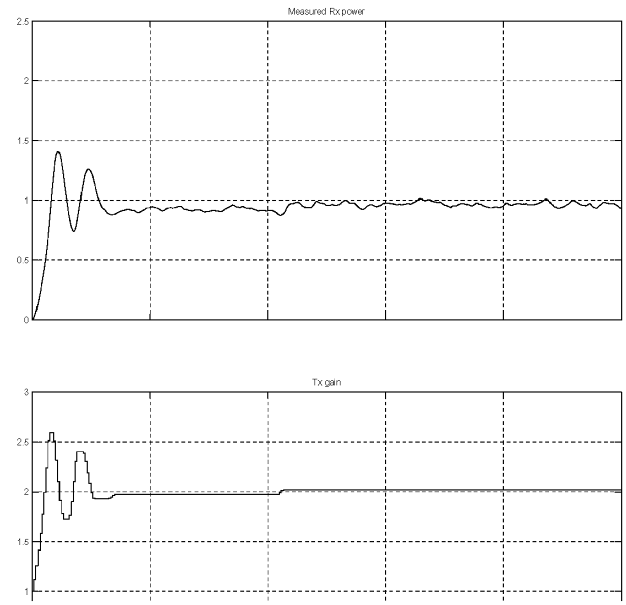


Fig. 6. Dynamic behavior of average power and transmitter gain factor with loop sampling factor DT/T = 1000 and rain attenuation value A of 6 dB

is negligible so as long as C/I > 6 dB.

D. Sensitivity to multipath channel's relative notch depth

Also simulated was the effect of the relative notch depth in Rummler's multipath model on the performance of the ATPC loop. We found no evidence of variation in the estimated received power for values up to B = 21 dB.

E. Sensitivity to ATPC loop return delay

Another result of our study is the impact of the ATPC loop return delay on the performance. The return delay td is the result of the receiver and transmitter antennas separated by a certain fixed distance d. As an example, for the symbol rate considered in this study (24 million symbols per second), a distance of 50 kilometers translates into a return delay of td = 167 msec or 4000 symbols. Our simulations confirm that, in general, the ATPC loop-sampling interval DT should not be smaller than the return delay td. Otherwise, the loop becomes unstable in a manner similar to that shown earlier for very small values of the loop-sampling interval DT. Figs. 9 and 10 illustrate the problem with the value DT/T = 500 in a 20 Km long link for which the normalized return delay value is given by t_d/T = 1600.

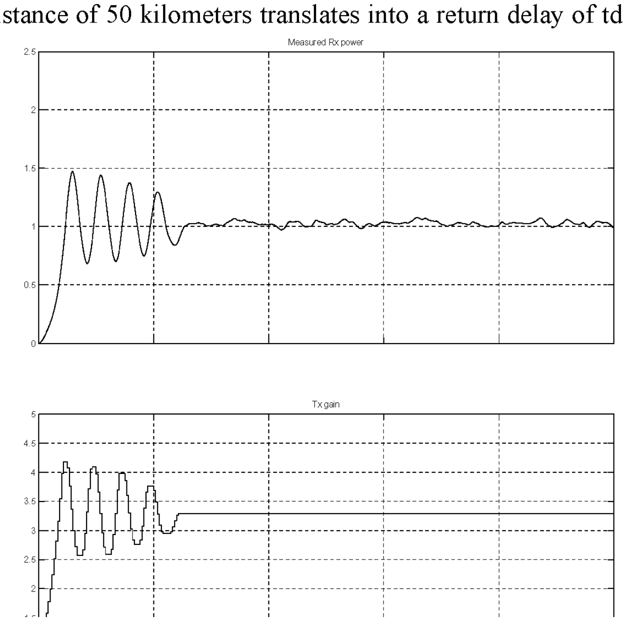


Fig. 7. Dynamic behavior of average power and transmitter gain factor with loop sampling factor DT/T = 1000 and rain attenuation value A of 10 dB

Our analysis of an ATPC-aided FWS link reveals the following:

1) Sensitivity to sampling rate and return delay: The sampling interval of the ATPC loop should be at least equal to the length of the impulse response of the averaging filter (used to estimate power at the receiver) plus the return delay. Failure to satisfy this requirement results in undesirable oscillations in transmitted power and possible loss of the link.

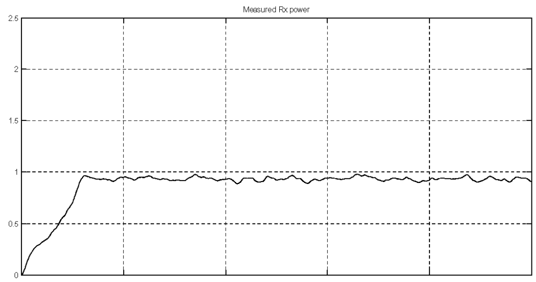
2) Sensitivity to rain attenuation: The larger the attenuation caused by rain, the greater the possibility that the ATPC loop will become unstable. This issue can be solved using a sufficiently low sampling rate in the loop.

3) Sensitivity to co-channel interference: Our simulation results suggest that the ATPC loop is insensitive to CCI as long as that the carrier-to-interference ratio satisfies C/I > 6 dB

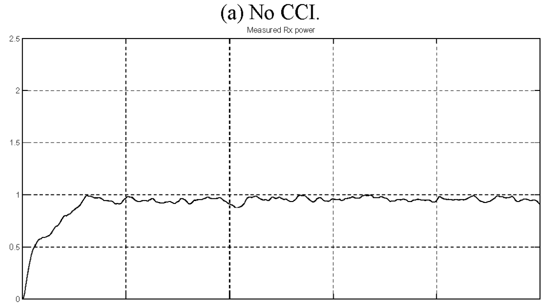
4) Sensitivity to multipath conditions: The simulations show no sensitivity of the ATPC loop to the multipath channel's relative notch depth.

V. CONCLUSIONS AND OBSERVATIONS

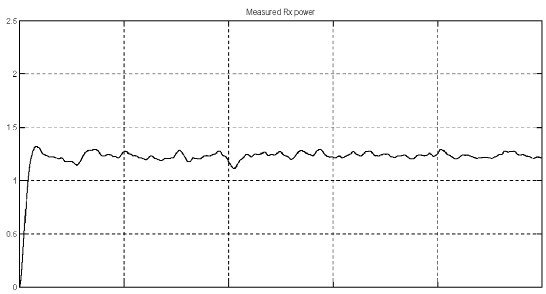
A computer model has been built that incorporates multipath effects in a fixed wireless link using a standard Rummler's model. This also includes an adaptive linear equalizer using the LMS algorithm and allows us to study parameter settings of ATPC loops. In our analysis, 64-QAM signals were employed. However, any other signal format and



(a) No CCI.



(b) C/I = 6 dB



(c) C/I = 0 dB

Fig. 8. Effect of CCI on estimated average power using DT/T = 1000 and rain attenuation value A = 6 dB

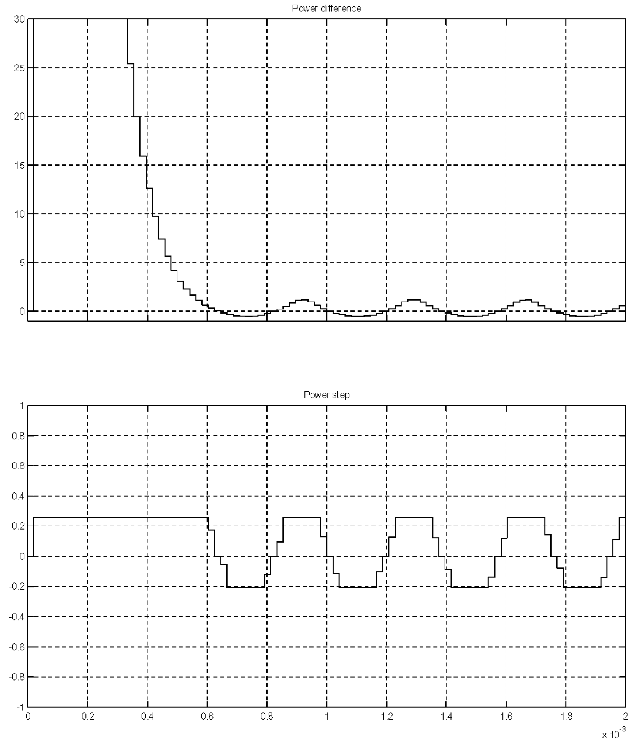


Fig. 9. Power difference $(1-P[n]^{-1})$ and power step DP, with DT/T = 500 and td/T = 1600

constellation size can be easily incorporated.

An important finding is that the sampling interval of the ATPC loop should be at least equal to the length of the impulse response of the averaging filter (used to estimate power at the receiver) plus the return delay. We have also found that an ATPC loop is insensitive to CCI provided that the value of the carrier-to-interference ratio (C/I) is at least equal to 6 dB.

An ATPC loop is also insensitive to the multipath channel's relative notch depth. Based on the study and results reported in this paper, the following important recommendations can be made: For frequency coordination purposes, mixed deployments (non-ATPC and ATPC) should be avoided. Full path clearance (0.6 of the first Fresnel zone for the worst month) must exist over an ATPC transmission path.

Careful calibration of antennas and amplifiers should always be required. ATPC power should not remain at the maximum level for more than certain amount of time. An ATPC system should not use bit error rate as a metric equivalent to average received power

REFERENCES

[1] Retrieved from http://en.wikipedia.org/wiki/Transmit_Power_Control

[2] FCC Chapter 47, Part 101: *Fixed Microwave Services*, Sec. 101.3, Oct. 1, 2002.

[3] *FCC Part 78, Revision to the Cable Television Relay Service (CARS)* (Part 78), Mar. 20, 2001.

[4] *FCC Part 74.636*, Oct. 1, 2003.

[5] C. Hardy and G. Macey, "Changes Affecting the Broadcast Auxiliary Spectrum: What you need to know," *Commsearch Report*, 2003. Available at http://commsearch.com/.

[6] *Microwave Fixed Services Frequency Coordination*, The Australian Communications and Media Authority, Spectrum Planning Branch, Spectrum Engineering Section, Canberra, Australia, Aug. 2006.

[7] *02-146 ExParte FCC WTB*, Cisco Systems, Inc., May 16, 2003..

[8] "Candidate Standard: ATSC Automatic Transmitter Power Control (ATPC) for the Data Return Link (DRL) Standard", *ATSC, doc. ATSC CS/TSG-696r1*, July 20, 2006

[9] "Amendment of Part 2 of the Commission's Rules to Allocate Spectrum Below 3 GHz for Mobile and Fixed Services to Support the Introduction of New Advanced Wireless Services, including Third Generation Wireless Systems," *FCC ET Docket No. 00-258*.

[10] "Fixed Radio Systems; Multipoint equipment; Radio equipment for use in Multimedia Wireless Systems (MWS) in the band 40.5 GHz to 43.5 GHz," *draft DEN/TM-4097 (2001-06), ETSI*, July 2001

[11] "Interference Relationships between Point-to-Multipoint Stations at about 28 GHz Authorized by Area License," *doc. IEEE 802.16.1c-00/12, IEEE*, June 2000.

[12] J.R. Norbury, "Towards the next generation LMDS systems architecture," *Telenor Report Telektronikk 1.2000*, pp. 17-27. Available at http://www.telenor.com/

[13] "On the sharing between point-to-point and point-to-multipoint FS and transmitting FSS earth station, GSO and non-GSO, in the 27.5-29.5 GHz band," Document 4-9S/TEMP/121-E, *International Telecommunications Union (ITU)*, April 24, 2002.

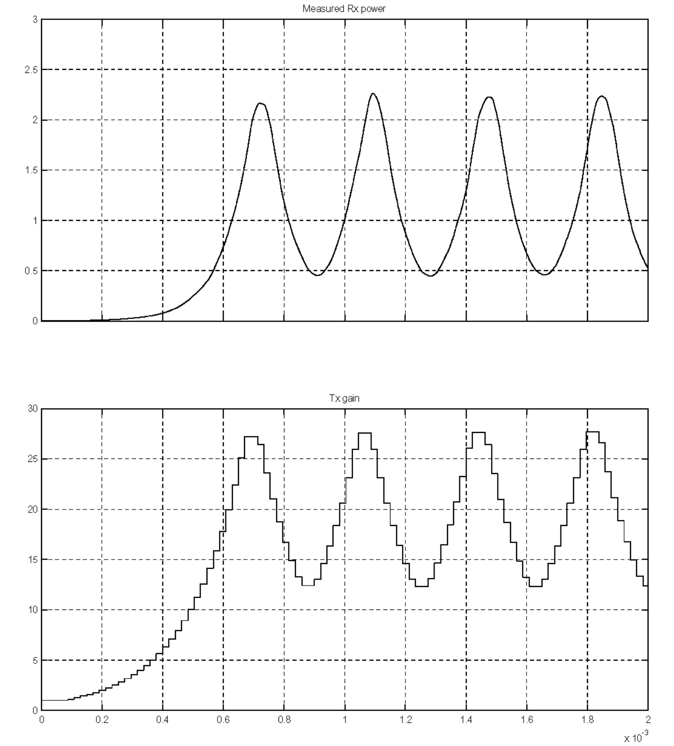


Fig. 10. Average power P[n] and transmitter gain factor G_T, with DT/T = 500 and td/T = 1600

[14] "Re-examination of the protection requirements for the Radio Astronomy Service in light of the Broadband Fixed Wireless Access Multimedia Wireless Systems proposed for the 42.5 - 43.5 GHz frequency band," *TSL Final Report RA/RAS-BFWA Annexes, Transfinite Systems Ltd*, Dec. 6, 2000.

[15] "Fixed Point-to-Point Radio Services with Digital Modulation Operating in the Frequency Ranges 5925 to 6167.58 MHz paired with 6182.42 to 6425 MHz and 6425 to 6760 MHz paired with 6770 to 7125 MHz," Report OfW 45, *Ofcom, UK*, Mar. 2006.

[16] *IEEE Std. 802.16.2-2001*, IEEE, Sep. 10, 2001.

[17] "Interference Protection Criteria. Phase 1 - Compilation from Existing Sources," *NTIA Report 05-432, U.S. Dept. of Commerce*, Oct. 2005.

[18] "Allocations and Service Rules for the 71-76 GHz, 81-86 GHz and 92-95 GHz Bands 81-86 GHz and 92-95 GHz Bands," *FCC WT Docket* No. 02-146, 2002.

[19] D. Bacon, "Rain modelling for radio system planning," *Ofcom, UK*, in: http://www.ofcom.org.uk/research/technology/overview/ese/atpc/.

[20] H. Sandler, "Power Control Assumptions for Coexistence Modelling," *document IEEE 802.16cc-99/14*, IEEE 802.16 Broadband Wireless Access Working Group.

[21] "A Review of Document ODTR 98/14 'Guidelines for Applicants for Point to Point Radio Link Licences in Spectrum Above 1GHz'," *The Office of the Director of Telecommunications Regulation,* Doc. No. ODTR 00/93, Dublin, Ireland, Dec. 2000.

[22] "Point to Point Radio Link Licences in Spectrum above 1 GHz – Guidance Notes," Doc. ComReg 98/14R3, *The Commission for Communications Regulation*, Dublin, Ireland, Dec. 2002.

[23] "Report of the Interference Protection Working Group," *Federal Communications Commission*, Spectrum Policy Task Force, Nov. 15, 2002.

[24] "Technical and Operational Requirements for LMCS," Appendix A, *RABC Fixed Wireless Communications Committee*, Dec. 8, 2000.

[25] "ECC Decision of 18 March 2005 on the use of the band 27.5-29.5 GHz by the Fixed Service and uncoordinated Earth stations of the Fixed-Satellite Service (Earth-to-space)," doc. ECC/DEC/(05)01, *European Radiocommunications Committee*, Mar. 2005.

[26] S.A. Callaghan, I. Inglis, P. Hansell, "Impact of introducing Automatic Transmit Power Control in P-P Fixed Service systems operating in bands above 13 GHz," *Ofcom contract 830000059*, Final Report, Feb. 28, 2006.

[27] D. Bacon, "Rain Modelling for radio system planning," *Proc. of the 2005 Rainmap Workshop*, Oxford, UK, Sept. 2005

[28] W.D. Rummler, "More on the Multipath Fading Channel," *IEEE Trans. Comm.*, vol. COM-29, no. 3, pp. 346-352, Mar. 1981

[29] W.D. Rummler, R.P. Coutts and M. Liniger, "Multipath Fading Channel Models for Microwave Digital Radio," *IEEE Comm. Mag.*, vol. 24, no. 11, pp. 30-42, Nov. 1986

[30] M.C. Jeruchim, P. Balaban and K.S. Shanmugan, *Simulation of Communication Systems*, 2nd ed., Kluwer Academic, New York, NY, 2000

[31] S. Salamah, *Transmit Power Control in Fixed Cellular Broadband Wireless Systems*, M.S. thesis, Carleton University, Ontario, Canada, 2000

[32] M. Cheffena, L. Erling Bråten, Terje Tjelta and T. Ekman, "Time dynamic channel model for broadband fixed wireless access systems," *Proc. of COST 280 Workshop on Propagation Impairment Mitigation for Millimetre* Wave Radio Systems, Prague, Check Republic, June 2005