Energy-Efficient Broadband Data Communications using White LEDs on Aircraft Powerlines

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Abstract — Broadband powerline communication has advanced through last decade and it is going to be a mature access technique in near future. Meanwhile, optical wireless communication through energy-efficient lighting LEDs has been investigated, recently. In this paper, it is shown that marriage of these two techniques creates an efficient delivery mechanism for fulfilling the promise of broadband access onboard an aircraft, while providing efficient and low-cost lighting. The potential capabilities of these two emerging techniques are examined.

***Index*:** Broadband communications, Capacity, PLC, WLED.

I. INTRODUCTION

Interest in new methods of multimedia delivery inside aircraft for providing seatback entertainment has grown in recent years [1,2]. This is due to the fact that installing avionic cables for such applications is not economical; needless to say, wiring increases the overall system weight. In [2], authors have proposed a MIMO scenario to realize broadband communications inside aircraft. However, radio frequency (RF) signals may interfere with the aircraft navigation systems. An alternative approach is to use the already-installed on-board powerline networks for providing both electricity and communications [3]. Another possible scenario is wireless optical communications. In particular, we can modulate the White Light Emitting Diodes (WLEDs) and use them as both reading lights and optical transmitters. A combination of these two ideas, i. e., powerline broadband communications and use of WLED for indoor communications has been described in [4].

The high-speed powerline communications (PLC) has been considered for many applications in recent years. Internet access, home networking, automatic meter reading (AMR) are just a few applications that benefit from the already installed powerline grids. These networks, despite their harsh characteristics from the communications view point, offer a fairly large throughput [5-6].

The main drawback of powerline networks is the possibility for electromagnetic interference (EMI) into/from other networks. Nevertheless, spectrum management and proper counter-measure design strategies can resolve this issue. Like other communications media, for the best performance, PLC requires a full characterization of channel impulse response. The challenges in characterizing aircraft powerlines are exacerbated, as this need to be done while aircraft is operating and the interfering sources are present. Another issue that makes powerline communications challenging is the time-varying nature of insertion loss and return loss, as the operation of each sensor will change the load line of the entire network.

Contribution of this paper is the modeling of aircraft powerlines and identifying the data delivery capacity bounds for these lines. We also consider Orthogonal Frequency Division Multiplexing (OFDM) as a transmission technique, leading to a high-speed backbone for multimedia delivery on aircraft powerlines. The paper is organized as listed below.

Following with the introduction section, a brief description on powerline communications and signal and systems models are presented in section II. Theoretical capacity bounds are introduced in section III along with a discussion on multi-tone modulation technique, as the candidate modulation for PLC. In section IV, WLEDs are considered as strong candidates for the future of lighting technology onboard aircrafts for their energy-efficiency. Simulation results based on actual measurements on a military plane are presented in section V, and we finish with our summary and conclusions, in the last section.

II. POWERLINE COMMUNICATIONS

A. Channel Model

Frequency response, H(f), of a matched transmission line can be expressed by means of a propagation constant, γ. In [5], voltage along the conductor at a distance *l* from the source, *V(l)*, is defined by:

$$V(l) = H(f)V(0) \tag{1}$$

$$H(f) = e^{-\gamma(f)l} = e^{-\alpha(f)l}e^{-j\beta(f)l} \tag{2}$$

where *V(0)* is the voltage at the source. By having the propagation constant, one may easily find a transfer function for powerline wire at a desired point on the conductor. As discussed in [5], each mode of coupling has a different propagation constant. Hence, there is a different frequency response for each mode.

Signal propagation does not take place along a direct path from a transmitter to a receiver in a powerline grid. Additional paths (echoes) also exist due to reflection at the network junctions. This creates a multi-path scenario with frequency selectivity, similar to a radio channel. Each arrived path at a receiver is weighted by a coefficient, *g*, which is the product of reflection and transmission coefficients of nodes along the path. As reflection and transmission coefficients are equal to or less than one, the weighting factors are equal or less than unity, as well.

With these weighting coefficients, we may express the grid as a summation of multiple paths with different length and weighting factors. The propagation along a wire follows (2), so one can easily express the multi-path network channel model as:

$$H(f) = \sum_{i=1}^{N} g_i e^{-\alpha(f)d_i} e^{-j\beta(f)d_i} \tag{3}$$

where N is the number of significant arrived paths at the receiver, d_i is the length of the *i*-th path and g_i is the weighting factor of the *i*-th path. This formulation is basically similar to what has been mentioned in [5], however, with a model for propagation constant that is appropriate for the particular powerlines.

Like in an automobile, GROUND is the body of aircraft. The power distribution grid on an aircraft uses several bus architectures connecting different sections of the aircraft, e.g., wings, cockpit, etc. Since there is no return line, characteristic impedance of a single line is poorly controlled.

If one overlays data transmission on top of power distribution lines, paths between sensor devices will see many various-length stubs. Every other device on that bus is wired to the single circuit breaker controlling that bus and from that common point power to all other devices on that bus originates. Even at moderate RF frequencies, each stub looks like a short circuit to ground at some frequency, thus more reason for multipath frequency-selective nulls.

B. Noise Model

The main noise sources identified on aircraft powerlines are as follow: colored background noise with a relatively low-power spectral density (PSD), which is a time-varying summation of all low power noise sources, narrowband noise of all AM signals, caused by broadcast stations, especially during take-off and landing, periodic impulsive noise synchronous to the main's frequency with multiple rates, and periodic impulsive noise asynchronous to the main's frequency caused by switching of rectifier diodes of power supplies. Asynchronous impulsive noise caused by switching transients in the network is the most harmful noise for data transmission. Its duration varies and the noise PSD level may reach 50dB above the background.

III. CAPACITY BOUNDS AND MULTI-TONE MODULATION

Over a highly dispersive channel, an efficient way to utilize the allocated bandwidth is to treat the channel as N independent sub-channels having a flat frequency response by choosing N to be large enough. It is desirable to have all sub-channels with the same probability of error, P_e. Constant P_e can occur when all sub-channels use the same class of error correction codes with a constant SNR gap Γ. The aggregate number of bits per dimension for this set of parallel channels is:

$$\bar{b} = \frac{1}{N}\sum_{n=1}^{N} b_n = \frac{1}{N}\sum_{n=1}^{N}\frac{1}{2}\log_2\left(1+\frac{\mathrm{SNR}_n}{\Gamma}\right) \qquad (4)$$

where N is the number of sub-channels and SNR_n is the signal-to-noise ratio of the *n*-th sub-channel. A single performance measure can be obtained to characterize a multi-channel transmission system. This measure is a geometric SNR that can be compared to the detection SNR of equalized transmission system. The asymptotic capacity of this multi-channel system is considered as a *single-carrier bound* and is obtained by :

$$b_s = \frac{1}{2}\log_2 \gamma_\infty^W\left\{1+\frac{\mathrm{E}(f)\left|H(f)\right|^2}{\Gamma N(f)}\right\}$$

where $H(f)$ is the channel transfer function, $N(f)$ is the noise power spectral density, $\mathrm{E}(f)$ is the signal power allocated at frequency *f*, and finally $\gamma_\infty^W(.)$ is defined as:

$$\gamma_\infty^W\{V(f)\} = \exp\left(\frac{1}{W}\int_0^W V(f)df\right) \qquad (5)$$

This is related to the so-called *Salz SNR*, where, often, used in practical system implementations to estimate the system noise margin (required SNR subtracted from achievable SNR) [7].

Maximizing the data rate, for a set of parallel sub-channels when the symbol rate is fixed, requires maximization of the achievable bit rate $\bar{b} = \sum_n b_n$ over E_l, the average power of each sub-channel. This is summarized as the following maximization problem, where H_n represents the n^{th} sub-channel transfer function.

$$\lim_{N\to\infty}\left(\underset{\mathrm{E}_n}{\text{maximize}}\sum_{n=1}^{N}\frac{1}{2}\log_2\left(1+\frac{\mathrm{E}_n\left|H_n\right|^2}{\Gamma N_n}\right)\right) \qquad (6)$$

$$\text{subject to} \sum_{n=1}^{N}\mathrm{E}_n = N\bar{\mathrm{E}}_x$$

A natural solution of this optimization problem is to use Lagrange multipliers. In this paper, we refer to the maximum value of this function, denoted as b_{WF}, the *water-filling bound*.

The solutions of water-filling equations for large *N* may produce b_n values that have fractional parts or are very small. Such small or fractional b_n can complicate encoder and decoder implementation. Alternative suboptimal loading algorithms approximate the water-filling solution, by imposing the integer values constrain on b_n. Basically, there are two types of loading algorithms - those that try to maximize data rate and those that try to maximize performance at a given fixed data rate [8].

Note that, in transmission over powerlines, the multipath effect will create deep nulls at some frequencies that require complicated equalization for broadband single-carrier systems. Time-varying impedance of powerline precludes fix equalization. The impulsive noise problem of the powerline channel can be solved by introducing long interleaver and power burst error correcting codes. A better solution for these problems is Discrete Multi-Tone (DMT) signaling. DMT is robust against time domain impulsive noise, frequency domain narrowband interference, and frequency selective fading, which are all the main features of powerlines. Interestingly, DMT can achieve the water-filling bound, and it can adopt the underlying technique to use bit-loading algorithms. An automatic adaptive algorithm is used in the DMT transceiver to turn off those sub-channels with a low signal-to-noise ratio.

However, it is more sensitive to frequency offset and phase noise, and has a relatively large peak-to-average power ratio. Channel state information (CSI) is also required to achieve the best performance. But most likely, CSI can be made available to the transmitters via Time Division Duplex (TDD). Fortunately, lots of research has been done on these problems in great details in the context of Digital Subscriber Line (x-DSL) communications.

IV. White LED Communications

WLEDs are considered as strong candidates for the future of lighting technology [4]. The reason is that LEDs offer very favorable characteristics such as high brightness, very low power consumption and high lifetime expectancy. Moreover, LEDs can be used as a wireless communications transmitter. This functionality of LEDs as a transmitter is based on a fast response time and modulation of visible light for wireless communications. There are several advantages using WLEDs for communications over Wi-Fi and IR for indoor communications:

- Installation is easier than most wireless systems.
- WLED communication does not need any band licensing because it does not cause or suffer from any electromagnetic interference. Whereas, there are always concerns in using Wi-Fi or any other RF communications systems regarding interference from or to other wireless communication systems. This property is of great importance for multimedia delivery onboard of an aircraft.
- Shadowing effect is so much less compared to IR case because LED light fixtures are distributed throughout the room.
- LEDs are less expensive than laser sources used in IR.
- Receiver obtains at least one strong Line-of-Sight (LoS) signal as the transmitters are on the ceiling. This is not the case in most IR transmission situations.

There are two different kinds of WLEDs in the market, single-chip WLED and multi-chip WLED. Single-chip is actually an Yttrium Gallium Arsenide (YAG) Phosphor coated blue LED. The combination of blue light of LED and yellow emission of phosphor then generates a white light source. This type of WLED has low cost and bright output.

Multi-chip WLED is in fact a combination of blue, green, and red LEDs and by changing the mixture ratio of these primary color LEDs, one can produce different colors. The response time of this type of LED is faster. However, it is hard to simultaneously modulate three LEDs. To solve this problem, one can modulate only one and place proper filter on the receiver site, so that the photo-detector can only receive the associated wavelength. Blue LED has two properties that make it the best candidate for modulation. First, it has the largest mixing ratio in producing the white color. Second, the photo-detector sensitivity is usually higher for blue wavelength. Fig.-1 shows single-chip and multi-chip and Fig.-2 demonstrates the spectrum of these two types. Since WLED serves as both reading light and optical transmitter, we have a line-of-sight link and each seat is considered to be a micro-cell. In order to derive the link budget equation we need to know the micro-cell configuration. The distance between sitting rows inside an airplane is called the seat pitch and is about 80 cm for an Airbus A-380 aircraft in economy class. The distance from armrest to armrest is called the seat width and is about 53 cm [10].

For any optical transmitter half-power (HP) angle is defined as the highest angle that the transmitter can illuminate. Similarly, for any optical receiver, field-of-view is defined as the highest angle within which the receiver can receive rays. Fig. 3 illustrates these angles.

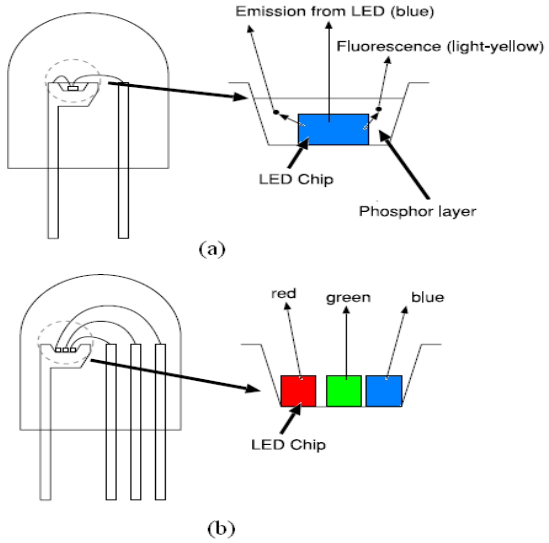

Fig. 1 (a) Single-chip and (b) multi-chip WLED.

The mathematical definitions of these parameters are given by equations (7) and (8).

$$HP = \tan^{-1}\left(\frac{r_1}{H}\right) \tag{7}$$

$$FOV = \tan^{-1}\left(\frac{r_2}{H}\right) \qquad (8)$$

For micro-cell scenario inside airplane, transmitters of large HP angle are not suitable since signals of two neighboring seats may interfere. Moreover, large HP angle introduces reflected beams into the system and hence delay spread increases, which in turn decreases the achievable rates. Fortunately, WLEDs are directional sources of light and their HP is 10-30 degrees. We choose HP angle to be 20 degrees, which corresponds to 13 dB directivity gain in the link budget equation. Wideband photo detectors that are used as receiver have small areas. Therefore, we need a concentrator system or lens to collect more power. Equation (9) relates receiver FOV and lens gain.

$$g(\theta) = \begin{cases} \dfrac{n^2}{\sin^2(FOV)}, & 0 \le \theta \le FOV \\ 0 \qquad , & \theta \ge FOV \end{cases} \qquad (9)$$

where *n* is refractive index of the lens.

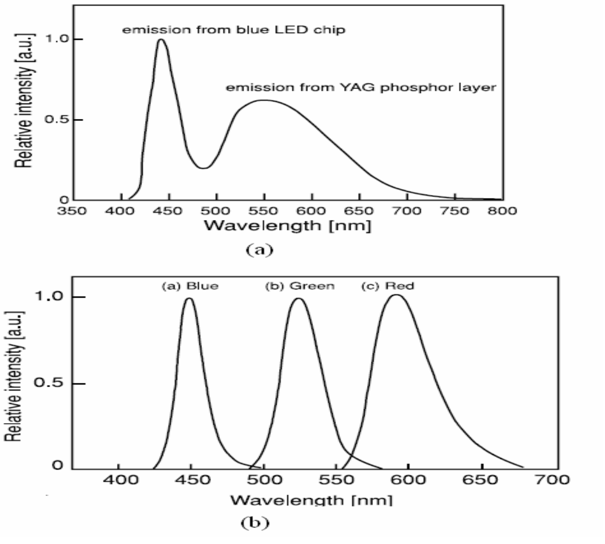

Fig. 2 Power spectrum of (a) single-chip WLED and (b) multi-chip WLED.

This shows that by increasing the FOV, lens gain decreases. Given the seat map of the plane, FOV can be as small as 11 degrees. Assuming *n*=1.5, lens provides an 18 dB gain.

From Friis formula, the path loss can be calculated as :

$$L = 10\log\left(A_{eff}\cdot\frac{I_{tx}}{P_{tx}}\cdot\frac{1}{d^2}\right) \qquad (10)$$

where A_{eff} is effective area of receiver, I_{tx} and P_{tx} are the transmitted intensity and power, respectively, and *d* is the distance between transmitter and receiver. Here, we need to collect as much power as possible; hence, we need a detector with a large effective area. However, increasing the photo detector area usually results in a large input capacitance and degradation in bandwidth. A trans-impedance amplifier with a common gate front-end will turn the dominant pole associated with the input capacitance into a non-dominant one and bandwidth values in the order of about 1 G Hz can be achieved with high-speed photo diodes such as HAMAMATSU S5973-01 [11].

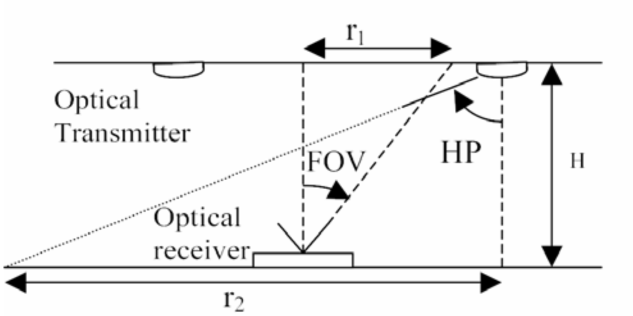

Fig. 3 Transmitter half power (HP) angle and receiver field-of-view (FOV).

The modulation schemes used in optical communications are usually intensity modulation techniques such as on-off keying (OOK) or pulse position modulation (PPM). Here, OOK modulation is used because of its simplicity and bandwidth efficiency and smaller pick to average power ratio. The bit error rate performance of OOK modulation is given by:

$$BER = Q(\sqrt{SNR}). \qquad (11)$$

Given a target bit error rate of 10^{-6}, the required signal-to-noise ratio (SNR) is about 22.6 or 13.54 dB. Since we have a Line-of-Sight (LoS) link and a large area optical receiver, thermal noise is often negligible compared to shot noise and the photo detector works in shot noise limited regime. Moreover, the background noise current is small compared to the signal current as a result of small

FOV and directive nature of WLEDs. Hence, SNR is given by [12]:

$$SNR = \frac{(RP_{rx})^2}{qI_{bg}R_b + qRP_{rx}R_b} \qquad (12)$$

where P_{rx} is received power, R is the detector resposivity, R_b is bit rate, I_{bg} is background noise current, and q is the electron charge. On board the aircraft, there is a small amount of background light since reading light and optical transmitter are both the same light source, namely; WLED.

Eye safety regulations [13], limits the WLED source power to a few hundred mW per LED. In [14] WLEDs of 20mW are considered for both lighting and communications.

Fig.-4 shows the required receive power as a function of achievable bit rate for different background light currents. Assuming a transmitted power of 20 mW and a path loss of about –40 dB, the received power is about –27.3 dBm and as Fig. 4 shows, bit rates up to 1 Giga bit per second are achievable for low background noise current levels per micro-cell.

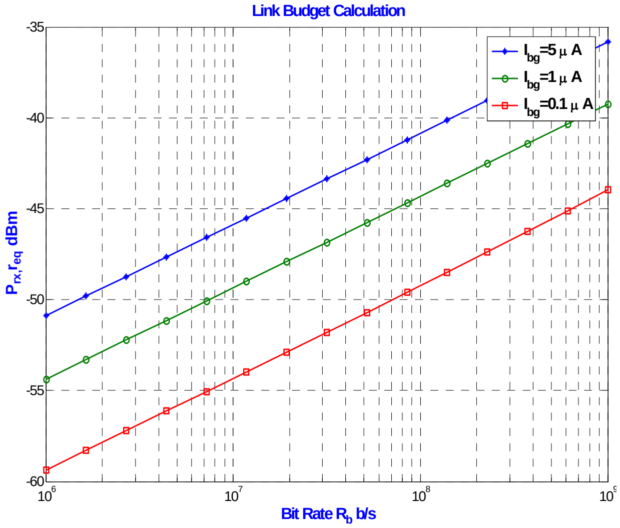

Fig. 4 link budget calculation

V. SIMULATION RESULTS

The characterization of aircraft powerline measured by Jones [3] is used in our simulation setup. The +28Vdc powerlines were characterized up to 100MHz. Two test links were chosen: Test Link 1 was from the left wing to the right wing, and Test Link 2 was from the left wing to under the cockpit on the right side. The power grids in this test were bus structure, wires carry all the electrical power to the sensors and devices, and their power returns were through the aircraft's chassis. Fig. 5 demonstrates the insertion loss characteristics of the military plane powerline cable.

The theoretical Shannon capacity of these links is shown in Fig. 6 for different transmit power levels. In this simulation, a background noise level N_0=-117 dBM/Hz is assumed. A maximum throughpat of 326Mbps can be achieved at P_s = 20dBm. Fig. 7 depicts the water-filling bounds of this channel for different system margin, which means the system designer may want to choose a specific reliability level, and seek to maximize the system margin to account for unforeseen sources of performance degradation.

VI. SUMMARY AND CONCLUSIONS

This paper discusses the potential capabilities of two emerging techniques, powerline communications and white LED wireless optical communications, for broadband access. Our investigations showed the particular military aircraft powerline network offers relatively high transmission capacity value per bus. Furthermore, it is shown that the reflections caused by mismatch throughout the network degrade the system performance.

Therefore, to attain higher data rate values; impedance matching in the network is necessary. Moreover, we discussed analysis of visible-light communication systems using white LEDs. These systems can offer lighting as well as optical transmission capability. To meet these criteria, we designed a white LED system for lighting and high data rate onboard aircraft communications, such that there is no blind spot for data communications, while the entire cabin area is lit nearly uniformly. It is shown that optical path difference can cause a signal distortion in high-speed data transmission. This distortion is highly dependant on the plane dimensions and system configuration. If a system is designed appropriately, this distortion can be minimized. For example, our proposed system in the worst case, limits the data rates to 1 Gbps.

Our investigations showed both systems could provide a relatively high data rate communications access for onboard aircraft networking. The overall capacity is bounded by the powerlines. Using better grade cables for powerlines in future generations of aircraft allows higher bit rates in data communications. Consequently, the integrated system of these two techniques will have an important impact as a new signal transmission system.

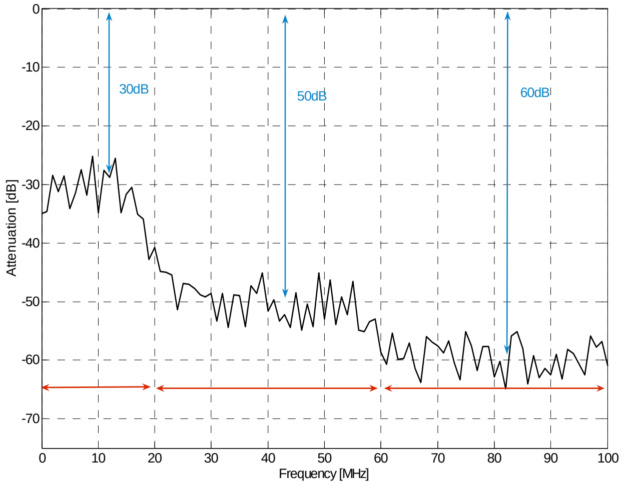

Fig. 5 Insertion loss characteristics of the military plane power line cable.

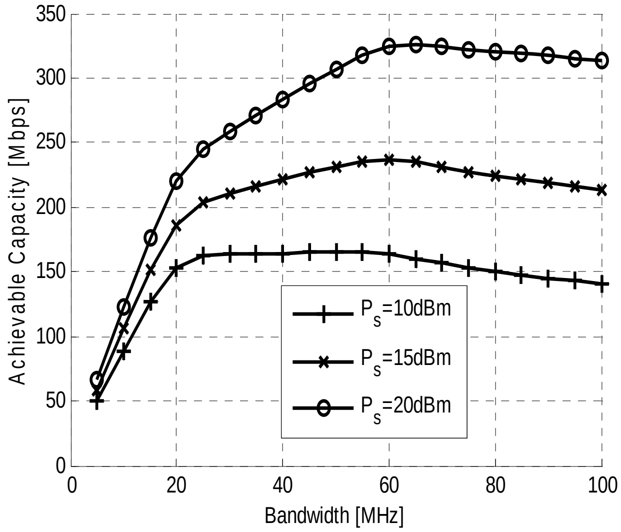

Fig. 6 Shannon capacity of aircraft's powerline vs. bandwidth for different transmit power levels.

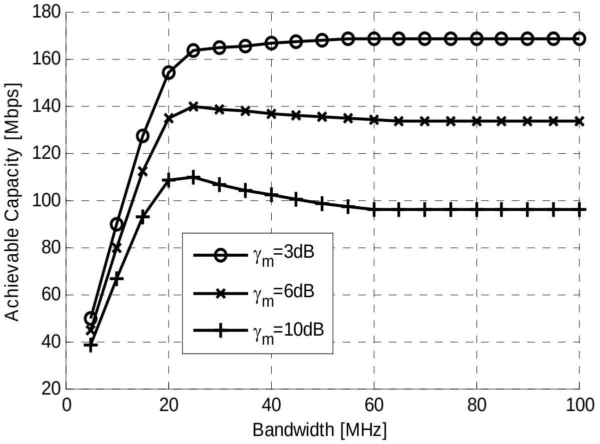

Fig. 7 Water-filling bounds of aircraft powerline communications for different system margin. P_s =15dBm, and g_c =5dB are assumed.

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