Study on Satellite Communications using Ultra Wideband (UWB) Signals

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Abstract In this paper, the possibility of satellite communication systems using a multiband UWB signal format is considered. For terrestrial short-distance high-speed communications, multiband UWB schemes are proposed in IEEE 802.15 TG3a and the discussion is ongoing at the standardization body. In the multiband UWB scheme, frequency hopping is adopted over 3.1 - 10.6 GHz, which is regulated by the FCC (Federal Communication Commission) of the U.S.A., and the bandwidth of one hopping spectrum (subband) is about 500 MHz. Multiband technology inherently has some suitable characteristics for terrestrial UWB such as applicability to variable transmission rates, avoidance of harmful interference to other systems, simple localizability of frequency allocations, and so forth. In this paper, a satellite communication downlink employing the multiband UWB signal transmission is considered. The total bandwidth is assumed to be 500 MHz in the allocation of the satellite downlink and it is divided into multiple subbands. We report the initial results of the study on the link budget calculation and the estimation of the signal transmission speed assuming multiband UWB signal transmission from a GSO satellite to the earth's surface.

1. Introduction

Recently, there has been much discussion on the use of UWB devices and the FCC (Federal Communications Commission) of the United States has defined the characteristics of UWB devices to open the door to utilizing the UWB devices for commercial use [1]. According to the FCC regulation, the emission level is restricted to as low as -41.3 dBm/MHz in 3.1 GHz – 10.6 GHz as described in the next section.

Although the current discussion on the UWB has mainly been done for terrestrial short distance communications, there is a possibility that UWB signal is radiated from satellites to the earth as one type of satellite services ("Satellite UWB"). It is shown that the satellite UWB has good property by which new satellite applications can be developed.

2. FCC Regulation on UWB

U.S. FCC has already regulated the UWB system, including the operating restrictions, authorizing the use of UWB devices on an unlicensed basis. Various applications are considered, such as communications, measurements, radar systems, and so forth. The followings are the spectrum and emission limitations of the regulation for handheld UWB devices, which are regarded as typical communication devices using UWB.

Bandwidth : Fractional bandwidth equal to or greater than 0.2,
or bandwidth equal to or greater than 500 MHz.

Radiated emissions :

0.96 - 1.61 GHz	<	-75.3 dBm/MHz
1.61 - 1.99 GHz	<	-63.3 dBm/MHz
1.99 - 3.1 GHz	<	-61.3 dBm/MHz
3.1 - 10.6 GHz	<	-41.3 dBm/MHz
10.6 GHz -	<	-61.3 dBm/MHz

Peak level of emissions : A peak level of the emissions contained within a 50 MHz bandwidth centered on the frequency at which the highest radiated emission is 0 dBm EIRP.

3. Satellite UWB

The satellite UWB system in this paper is a fixed satelite system, which employs a UWB type signal for downlink transmission. Figure 1 shows the conceptual view of satellite UWB system using the Ku-band. The UWB signal is usually characterized by transmitting very short monocycle wavelets or pulse modulated carrier. As presented in Section 2, the signal bandwidth of the terrestrial UWB devices is very wide at more than 500 MHz. The assumed bandwidth used in a satellite UWB system is 500 MHz.

The satellite UWB has suitable characteristics for exploring new satellite services from the following perspectives:

- The UWB signals can be overlaid on the existing narrowband spectrum. This is expected to contribute to increasing spectrum efficiency of the satellite systems.
- The terrestrial UWB devices can be utilized for satellite UWB applications, which would reduce the cost of the satellite system. Terrestrial UWB devices are expected to become very popular and mass-production of the terminals will greatly reduce the production cost of the hardware.

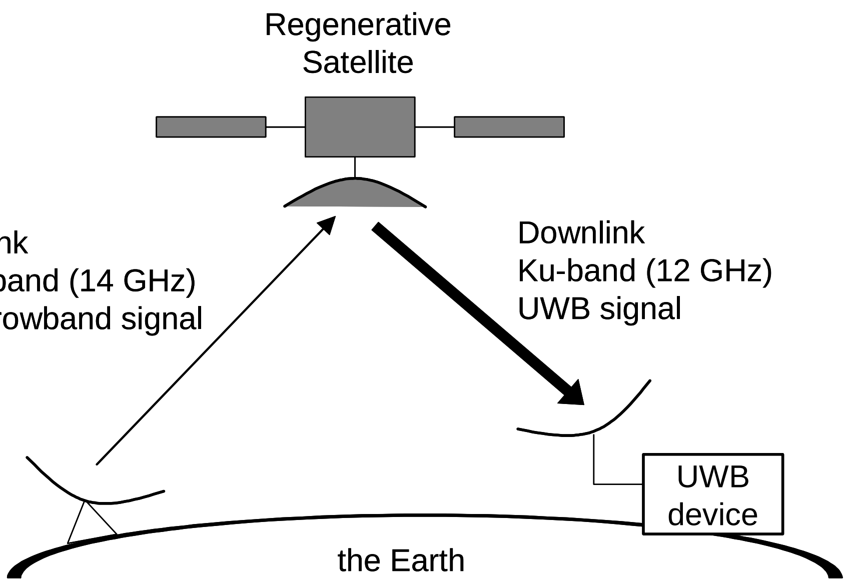

Fig. 1. Conceptual view of satellite UWB system using Ku-band.

4. Link budgets

In the satellite UWB systems, if the power transmitted from a satellite to the earth is at the same level as the terrestrial UWB devices, the received signal on the earth is very low, and the transmission speed is limited to very low. Therefore, higher power, which is comparable to those with existing satellite transponders, is assumed to be transmitted from the UWB satellite. This paper assumes the satellite transmission power as being 108 W (20.3 dBW) and the transmitting satellite antenna diameter as 1.27 m. When these transmission characteristics are adopted by the satellite to transmit the UWB signal to the earth, radiated EIRP from the satellite is much greater than that of the terrestrial UWB. But the signal power density received at the earth's surface is assumed to be comparable to or smaller than that of the terrestrial UWB devices as described below.

Link budgets of the downlink are estimated in the case where 500 MHz in the Ku-band is assumed as the downlink spectrum. Table 1 summarizes the downlink link budget of the system.

The free-space path loss for the distance of 3 m at the center frequency of 6.85 GHz, a typical value for the terrestrial UWB devices using the 3.1 - 10.6 GHz spectrum, is around 60 dB. In the terrestrial UWB devices, the power density, which is given by [EIRP]-[Path Loss] in dB scale, at a distance of 3 m from a transmitter is -101.3 dBm/MHz. The table shows that the power level of the satellite UWB signal received at the earth's surface (-148.1 dBm/MHz) is much smaller than the signal level at the distance of 3 m of the terrestrial UWB. Therefore, other services shall not be affected by the satellite UWB systems.

Table 1. Downlink link budget.

Center frequency	12	GHz
Bandwidth	500	MHz
Transmission power	20.3	dBW
Satellite antenna diameter	1.27	m
Satellite antenna gain (efficiency = 60%)	41.8	dBi
EIRP	65.1	dBm/MHz
Link margin	5	dB
Rain margin	3	dB
Path loss to the earth surface (at 12 GHz)	205.2	dB
Power density at earth surface	-148.1	dBm/MHz

5. Throughputs

5.1. *M*-ary PAM UWB

M-ary PAM(Pulse Amplitude Modulation) is the modulation scheme that the information could be modulated with +/-M variations. The pulse has a short duration, and its energy concentrates within the bandwidth of the satellite downlink, in the satellite UWB (Fig. 2).

Results of the research have been reported for the communication performance of the terrestrial UWB devices. Here, the performance is discussed using the approach presented in Ref. [2].

A coherent detection is assumed as the demodulation scheme. The symbol error probability P_M of *M*-ary PAM is given by

$$P_M = \frac{M-1}{M} erfc\left(\sqrt{\frac{3}{M^2-1} \bullet \frac{E_s}{N_0}}\right). \qquad (1)$$

And the probability of a bit error P_b is [3]

$$P_b = \frac{1}{k} P_M, \qquad (2)$$

where k is the number of bits, which are transmitted in one symbol, i.e. k=log2M. Using Eqs. (1) and (2), the required E_s/N_0, a signal power per symbol to noise power density ratio, can be calculated. Table 2 shows the required E_s/N_0 for the bit error rate of 10-3.

Table 2. Required E_s/N_0 for *M*-ary PAM.

M	Required E_s/N_0 [dB]
2	7
4	13.75
8	19.77
16	25.5

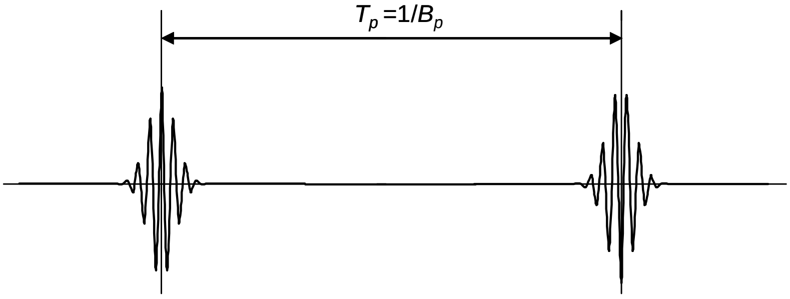

Fig. 2. Symbol of *M*-ary PAM.

On the other hand, E_s/N_0 is also presented by the following equation.

$$E_s/N_0 = P_{ave}T_p/N_0 = [P_{sd}/N_0]\times[B_s/B_p], \qquad (3)$$

where,

P_{ave}: Average received power,
T_p: Pulse repetition period,
P_{sd}: Average power spectral density,
B_s: Equivalent occupied bandwidth, and
B_p: Pulse repetition frequency.

Equation (3) indicates that the pulse repetition period T_p becomes larger as requied E_s/N_0 becomes larger. Take the receiver noise figure N_F into consideration, the pulse repetition frequency B_p can be written as

$$B_p = [P_{sd}/N_0]\times B_s / N_F /[E_s/N_0]. \qquad (4)$$

Using log2*M* equal to a number of bits transmitted by one pulse, the achievable throughput *R* can be calculated as

$$R = B_p \times \log_2 M \cdot \qquad (5)$$

Assuming free-space propagation between a satellite UWB transmitter and a receiver, and also assuming P_{sd}=-208.1 [dBm/Hz], B_s=500 [MHz] from Table 1, N_0=-174 [dBm/Hz] at room temperature (17[℃]), and N_F=6 [dB], the achievable throughput can be calculated from Eqs. (4) and (5). Table 3 summarizes the achievable throughput of the *M*-ary PAM UWB transmitted from a satellite using the Ku-band.

Table 3. Achievable throughput of *M*-ary PAM UWB.

[bit/s]

	2-ary	4-ary	8-ary	16-ary
0 [dBi] (Same as terrestrial UWB)	9.96 k	4.21 k	1.58 k	563
5.0 [dBi] (Patch antenna)	31.5 k	13.3 k	4.99 k	1.78 k
19.8 [dBi] (10 cm dish)	951 k	402 k	151 k	53.7 k
33.7 [dBi] (50 cm dish)	23.3 M	9.87 M	3.70 M	1.32 M
39.8 [dBi] (1 m dish)	95.1 M	40.2 M	15.1 M	5.37 M

5.2. Multiband UWB

In the terrestrial UWB, multiple transmission schemes adopting frequency-hopping over 3.1 - 10.6 GHz have been proposed at IEEE802.15 TG3a. The mission of the standardization body is to define the physical layer specification for WPAN (Wireless Personal Area Network). Multiband UWB is one of the frequency hopping schemes and has the feature of bit rate scalable with the occupied frequency.

Figure 3 shows an example of the symbol structure of the multiband UWB [4]. The symbol pulse consists of subpulses. And subpulses are hopping over multiple frequency bands. Data is encoded into the sequence pattern of bands and phase information of the subpulses. The number of bits (N) transmitted by one symbol is

$$N = \log_2({}_S C_B \bullet {}_T P_B \bullet 2^{BP}), \qquad (6)$$

where,

S: Number of frequency bands,
T: Number of subpulse time slots in a pulse,
B: Number of non-zero entries, and
P: Number of polarity bits.

${}_S C_B$ and ${}_T P_B$ indicate combination and permutation, respectively. In Eq. (6), data of log2(${}_S C_B \cdot {}_T P_B$) bits are transmitted by the sequence pattern, and data of log2(2BP) (=BP) bits are transmitted by the phase information of the subpulses.

Assuming S=T=B, Eq. (6) can be written as follows;

$$N = \log_2(S!) + SP. \qquad (7)$$

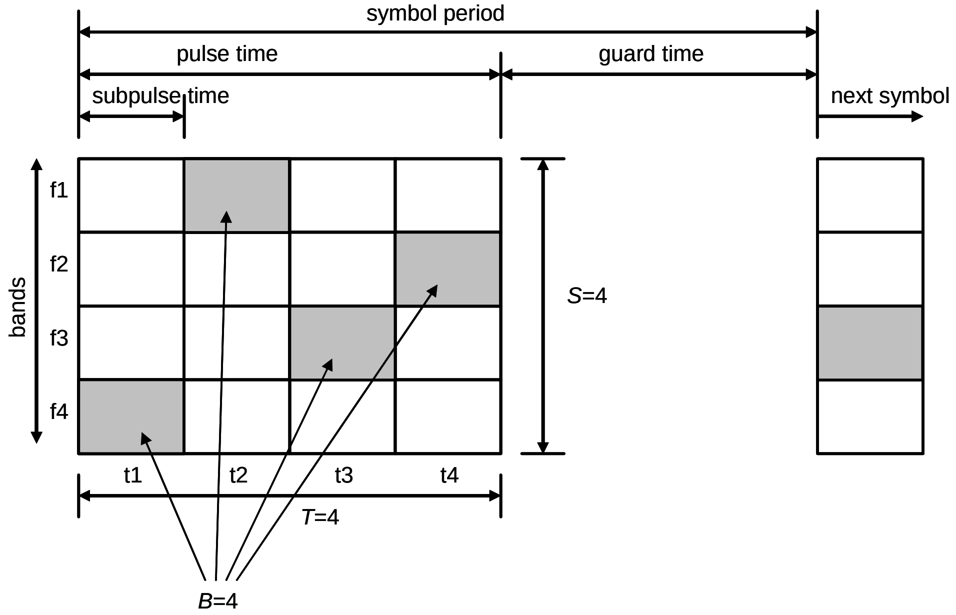

Fig. 3. Example of symbol structure of multiband UWB.

Upper bound of the subpulse error probability P_s of multiband UWB, which uses S bands, is given by

$$P_s = 4(S-1)Q\left(\sqrt{\frac{2E_{sp}}{N_0}}\right), \qquad (8)$$

where,

S: Number of frequency bands,
E_{sp}: Energy per subpulse, and
N_0: Noise spectral density.

The relation between the energy per subpulse E_{sp} and the energy per symbol E_s is

$$E_s = E_{sp} \times S. \qquad (9)$$

Using Eqs. (8) and (9), the required E_s/N_0 can be calculated. Table 4 shows the required E_s/N_0 for the subpulse error rate of 10-3.

Table 4. Required E_s/N_0 for S－bands UWB

S	Required E_s/N_0 [dB]
4	14.5
8	18

Similar to the M-ary PAM, the pulse repetition frequency B_p can be written as

$$B_p = [P_{sd}/N_0] \times B_s / N_F / [E_s/N_0]. \qquad (10)$$

Because the number of bits in one symbol is expressed by Eq. (7), the achievable throughput R can be calculated as

$$R = B_p \times [\log_2(S!) + SP]. \qquad (11)$$

Assuming the same as the M-ary PAM P_{sd}=-208.1 [dBm/Hz], B_s=500 [MHz], N_0=-174 [dBm/Hz] and N_F=6 [dB], the achievable throughput can be calculated from Eqs. (10) and (11). Table 5 presents the achievable throughput of the S-band UWB transmitted from a satellite using the Ku-band.

Table 5. Achievable throughput of S-bands UWB.

[bit/s]

	4-bands		8-bands	
	BPSK	QPSK	BPSK	QPSK
0 [dBi] (Same as terrestrial UWB)	15.2 k	22.3 k	18.4 k	28.4k
5.0 [dBi] (Patch antenna)	48.1 k	70.5 k	58.3 k	78.3 k
19.8 [dBi] (10 cm dish)	1.45 M	2.13 M	1.76 M	2.36 M
33.7 [dBi] (50 cm dish)	35.6 M	52.3 M	43.2 M	58.1 M
39.8 [dBi] (1 m dish)	145 M	213 M	176 M	236 M

5.3. Analysis

Table 3 shows that the transmission speed of the binary PAM up to 950 kbit/sec can be realized using a very small user antenna such as 10 cm. And, when a larger antenna is utilized, considerably large throughput is realized.

In Table 4, by adopting the multiband UWB scheme, a satellite UWB transmission speed of over 1 Mbit/sec can be achieved using a 10 cm dish antenna. And throughput over 100 Mbit/sec is realized by utilizing a 1 m dish antenna.

In the process of conducting the transmission speed, the bit error rate of 10-3 is used at M-ary PAM, and the subpulse error rate of 10-3 is used at the multiband UWB. In the multiband UWB scheme, data is transmitted by the sequence pattern of bands and phase information of the subpulses, so the relationship between the subpulse error rate and the bit error rate is difficult to be solved. As described above, in calculating the transmission speed, the error rate assumption of M-ary PAM and multiband UWB differs, so it is difficult to compare the transmission speeds directly. However, it can be said that the satellite UWB using M-ary PAM or multiband UWB can offer sufficiently high transmission speed. It indicates that these schemes have the possibility to be adopted in fixed satellite communications.

6. Conclusion

Technical consideration and performance analysis are conducted for the satellite UWB system. The system could realize sufficient throughput with a small antenna in addition to its inherent suitable characteristics to widely broadcast information to many users simultaneously.

ACKNOWLEDGMENTS

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