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Title	**Link Budget on the Uplink for IEEE 802.16e**
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Re:	Ballot #14a
Abstract	This contribution outlines the severity of the link budget on the uplink of broadband mobile wireless systems and proposes a potential solution.
Purpose	Information
Notice	
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Patent Policy and Procedures	

Link Budget on the Uplink for IEEE 802.16e

Overview

This contribution outlines the severity of the link budget on the uplink of broadband mobile wireless systems and proposes a potential solution. The combination of wide channel bandwidths (up to 20 MHz or more) and practical constraints on the output power of portable, battery operated devices leads to severe link budget problems on the uplink. Since in order to be commercially attractive, cellular systems need to be able to be deployed with relatively large cell sizes (e.g., at least a 2-km radius), alternative solutions must be found to ensure good link quality and high data rate capabilities on the uplink.

Assumptions

The path loss model used is the one defined by the ITU for the evaluation of cellular systems [1]. The path loss L is given (in dB) by

$$L = 40(1 - 0.004h_b)\log(d) - 18\log(h_b) + 21\log(f) + 80$$

where h_b is the base antenna height above the average rooftop level (in m), d is the base to mobile separation (in km), and f is the carrier frequency (in MHz). This path loss model gives an attenuation values consistent with results reported in [3] for non line-of-sight propagation.

In this contribution, two types of mobile units are considered:

- **Portable**: Effective Isotropic Radiated Power (EIRP) of 100 mW
- Personal Digital Assistant (**PDA**): EIRP of 500 mW.

Note that an OFDM signal has a peak-to-average power ratio (PAPR) on the order of 10 dB, so these transmitted power levels correspond to a power amplifier with a 1W and 5W peak power capability, respectively. Note that these values are already very high for battery-operated devices. Furthermore, it might be difficult to go to higher transmit powers (EIRP) because of the FCC regulations [2].

The baseline link budget parameters are given in Table 1. The cell radius can be 2, 4 or 8 km, with 2 km probably being the most sensible deployment option. The target received SNR at the base station (BS) is either 5 dB or 10 dB. Continuous transmission is assumed. Note that the values used here are chosen to illustrate how tight the uplink link budget is, and are not intended to be definitive values for any particular device or deployment.

Table 1. Baseline parameters for the link budget evaluation.

Frequency (GHz)	3.5
Antenna height (m)	28
SS av. EIRP (dB)	20 or 27
BS Antenna Gain (dBi)	16
BS Noise Figure (dB)	5
Link Margin for Shadowing (dB)	10
Cell radius (km)	2, 4 or 8
Link Target SNR (dB)	5 or 10

Link Budget Analysis

The uplink performance is evaluated in terms of *useful bandwidth*. The useful bandwidth is defined as the maximum spectral bandwidth that a SS can transmit while still meeting the target received SNR over the occupied bandwidth (e.g., a lower spectral bandwidth concentrates the total transmit power into a smaller bandwidth and provides a corresponding increase in the received SNR). This performance indicator has the advantage of being independent of the total system bandwidth. Thus, the results presented here are not tied to any particular channel bandwidth assumptions. The useful bandwidth can be translated into a rough idea of the achievable channel data rate if the target SNR is mapped to an appropriate modulation and coding scheme.

Table 2 gives the useful bandwidth for a target SNR of 10 dB and cell radii of 2, 4 and 8 km. Clearly, the link budget severely limits the useful bandwidth. For a cell radius of 2 km, a portable unit can get only 40 kHz and a PDA unit can only get only about 200 kHz. If the system bandwidth is 20 MHz, a 40 KHz allocation represents only 0.2% of the total available bandwidth.

Table 3 is essentially the same as Table 2, but for a target SNR of 5 dB. Reducing the target SNR improves the useful bandwidth by roughly a factor of 3 (but requires the use of a lower modulation/coding scheme). Still, the amount of allocated bandwidth remains very small.

Table 2. Useful bandwidth (in kHz) for a target SNR of 10 dB and varius cell radii.

EIRP (dBm)	***20***	***27***
R=2 km	39.8	199.3
R=4 km	3.4	17.0
R=8 km	0.29	1.45

Table 3. Useful bandwidth (in kHz) for a target SNR of 5 dB and varius cell radii.

EIRP (dBm)	***20***	***27***
R=2 km	125.8	630.4
R=4 km	10.74	53.8
R=8 km	0.9	4.6

The severe link budget constraints of the uplink lead to various problems:

- The **range is very limited**. It is probably difficult to deploy cells with a radius of 2 km when high data rates are desired on the uplink.
- The limited amount of useful bandwidth means low bit rates, hence **latency** can become a significant issue. Units with a low EIRP would require transfer times well over 100 ms to send a standard 1500-byte IP packet. This high latency on the uplink can lead to a higher latency on the downlink as well.

System Simulation SNR Distribution Analysis

While the link budget analysis is useful, it only focuses on the edge of the cell. In this section, we look at all of the users present in the cell in order to show that thermal noise is a very significant issue for most of the users. For this section, the mobile EIRP is 100 mW, the shadowing standard deviation is 10 dB, and for the initial C/N analysis the channel bandwidth is 20 MHz. Figure 1 shows the CDF of the C/N aggregated over all the users present in the sector. As is apparent on Figure 1, more than 85% of the users have a negative C/N. It is therefore very unlikely that a user could get the entire 20 MHz uplink bandwidth (unless this user is very close to the BS).

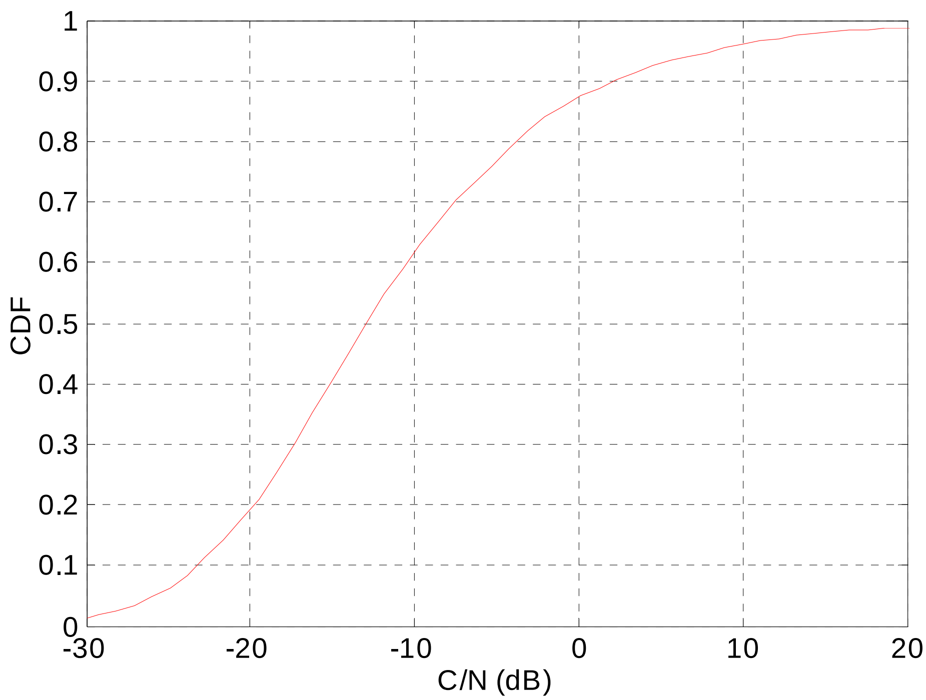

Figure 1. C/N distribution.

However, most users will not need the entire 20 MHz bandwidth very often. Hence it is beneficial to look at the useful bandwidth one unit can get. Figure 2 shows the CDF of the useful bandwidth over the sector (with a target C/N of 5 dB). Nearly 2/3 of the whole population is restricted to useful bandwidths lower than 1 MHz (which is less than 5% of the total bandwidth).

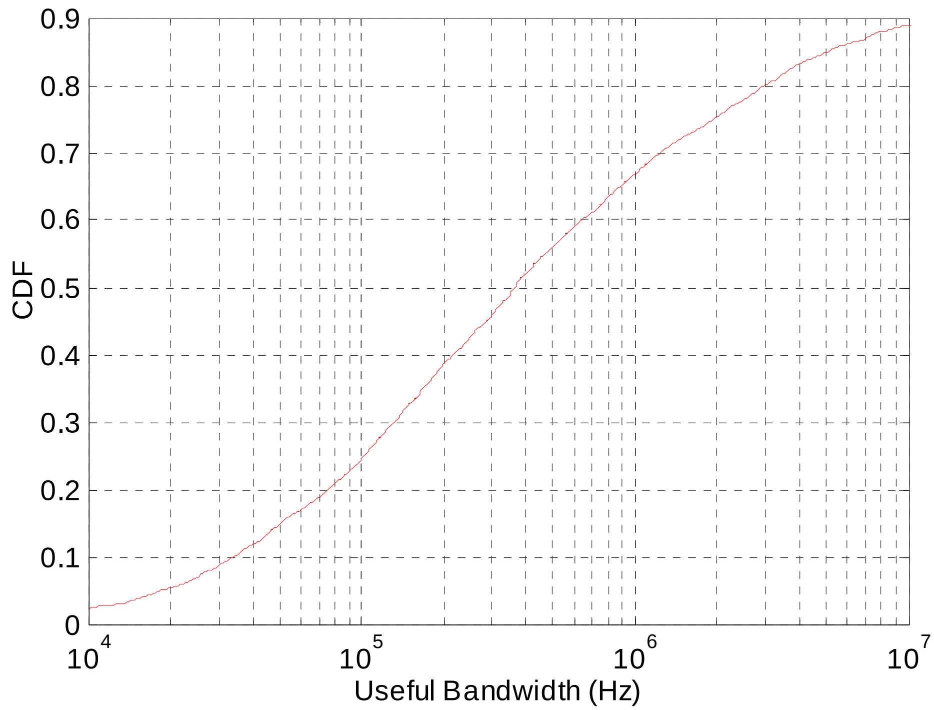

Figure 2. Useful bandwidth (target C/N of 5 dB).

Clearly, there is significant room for improvement in the uplink performance. Note however that some of the conventional solutions may not be helpful in this scenario. For instance, increasing the transmit power may not be practical for portable devices due to the high PAPR of the OFDM signal as well as FCC EIRP limitations. The use of adaptive antenna arrays (AAS) at the BS would definitely be helpful. Assuming eight antennas per sector, a gain of 6-7 dB is expected over the usual two-antenna BS receiver case (note that the effect of a 7 dB increase in link budget can be seen by comparing the first and second columns in Tables 2 and 3). This performance improvement would increase the link efficiency, but cannot be used to increase the cell size because AAS support is *optional* for the subscriber stations (i.e., non-AAS-capable SSs must be accommodated in the cell). Also, if the multiple antennas are used to support SDMA or MIMO in the uplink, the link budget gain will be significantly lower than the case where they are used solely to improve link quality.

A Possible Solution: Uplink Relaying

One way to increase the uplink range while maintaining a high bit rate is to deploy repeaters or relays for the uplink. Relays can be used in a cellular system to increase the signal strength in areas at a large distance from the main base station. They can also be used to improve in-building coverage, or to improve coverage in "dead-spots" caused by terrain characteristics. The general idea of repeaters/relays is not new, but the challenges of broadband propagation physics are causing people to take a new look at the idea. Here the relay is assumed to be digital rather than a conventional analog repeater. A digital relay demodulates and decodes its received signal and then re-encodes and re-transmits the data on a separate channel resource (e.g., in a following frame for an in-band relay or on a different RF channel for an out-of-band relay).

In this section, the potential benefits of uplink relaying are explored. In general, the relaying function could be provided by another SS (mobile ad-hoc relay) or a special roof/pole mounted dedicated unit (fixed relay). Here, we will focus on the latter case because it is much simpler to integrate into an existing standard, and has the minimal impact on the SS. In fact, it should be possible to design the relaying scheme such that a normal 802.16e SS can use a relay without even being aware that a relay is deployed in the system (i.e., a transparent relay).

The basic deployment scenario examined here is shown in Figure 3. The cell radius is 2 km. Each cell has three sectors, and three relays are deployed in each sector. All the relays are placed on a 1.4 km cell radius every 40 degrees. Note that while the relays locations are reasonable, no effort was made to optimize them. The receive antenna gain of the relay is 9 dBi, and the transmit antenna is assumed to be a directional antenna pointed towards the BS. Since the relays can use a directional transmit antenna and may be able to transmit with higher power than a mobile SS, we assume a relay-to-base link C/N of 27 dB. This effectively makes the SS-to-relay link the limiting factor in terms of the link quality of any relayed uplink transmission.

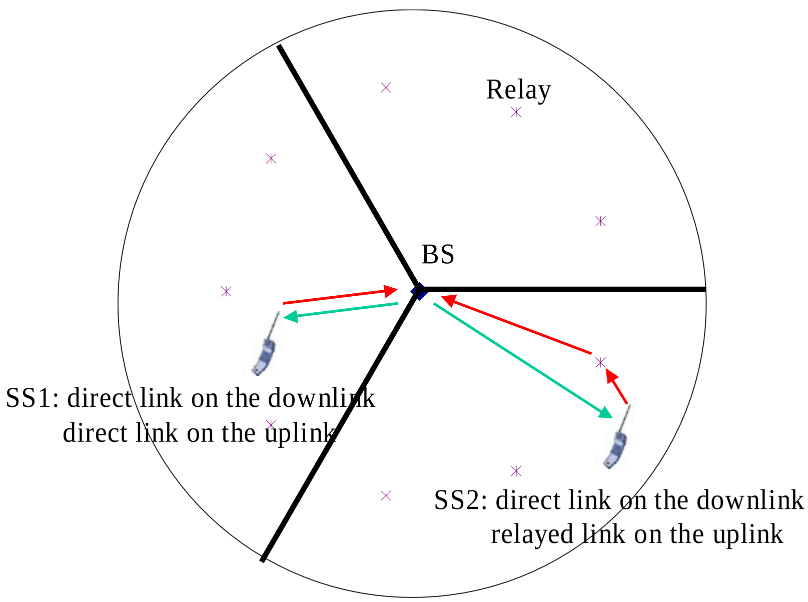

Figure 3. Deployment scenario for the relays.

In-Band Relaying is used. This means that the mobiles and the relay operate on the same frequency band, and share the uplink channel resources. In a TDD system, a relay cannot listen and transmit at the same time. Consequently, the mobile's duty cycle is reduced. In this study, it is assumed that the mobile's duty cycle is 100% for a non-relayed transmission, and 50% for a relayed transmission: on a first time slot, the mobile transmits and the relay listens, and on a second time slot, the relay transmits and the mobile is idle. Note that more advanced resource allocation schemes would provide a better duty cycle (and hence a higher throughput): for instance, since the relay->BS link is generally better than the mobile->relay link, the relay needs less time than the mobile to transmit the same amount of information (e.g., the relay->BS link could use higher order modulation). A mobile can transmit either directly to the BS or to a relay, depending on the link quality. The relay is activated only when doing so improves uplink the C/N as compared to a direct mobile->BS link. Note that however, on the downlink, a direct BS->SS link is always used.

Figure 4 shows the C/N improvement with relaying for the described scenario. In this case, relaying yields about a 10 dB improvement in C/N.

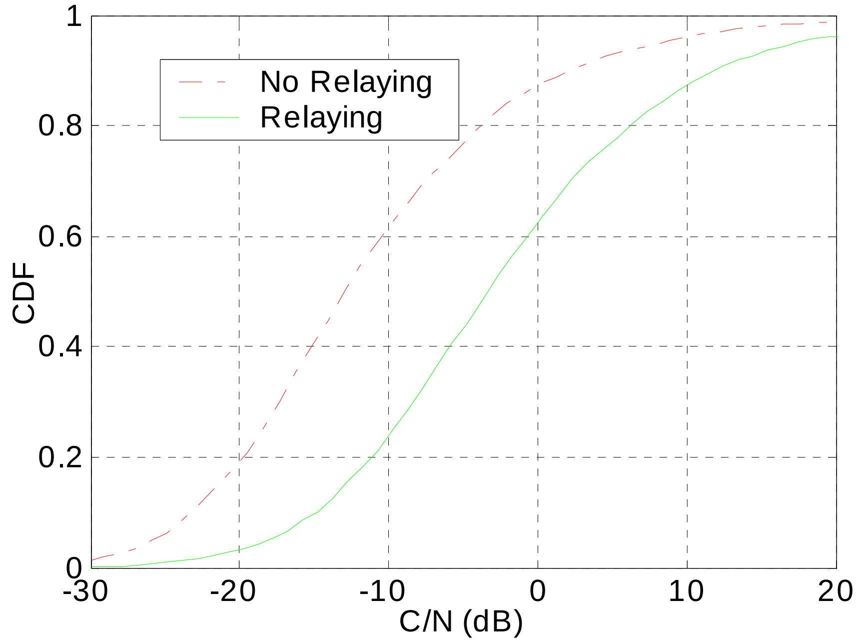

Figure 4. C/N improvement with relaying.

The improvement in useful bandwidth provided by the relaying scheme is shown in Figure 5. In these results, the useful bandwidth with relaying was divided in half to reflect that whenever relaying is activated for a SS, the SS only transmits on 50% of the uplink assignment, and the relay transmits on the other half of the assignment. For these results, a relay is activated only when doing so provides an increase in the useful bandwidth (after taking the duty cycle reduction into account). Even with the duty cycle reduction taken into account, relaying yields about a 10x improvement in useful bandwidth. As noted earlier, better resource allocation schemes could be used to reduce the amount of transmit time needed for the relay’s transmission, leading to further improvements compared to the results in Figure 5.

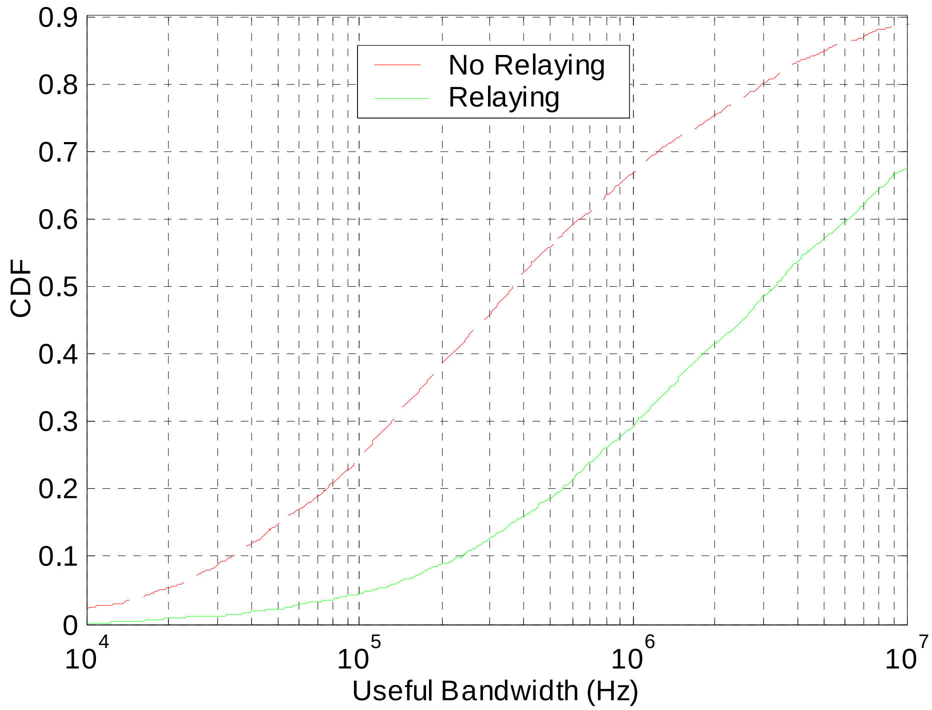

Figure 5. Useful bandwidth improvement with relaying.

Conclusion

The link budget on the uplink is severe enough to drastically reduce the system performance, and the poor uplink performance could also indirectly impact the downlink performance/latency. Adaptive antennas would be helpful, but simple alternative options such as uplink relaying should also be enabled in the 802.16e standard.

References

[1] Rec. ITU-R M.1225, "Guidelines for evaluation of radio transmission technologies for IMT 2000," 1997.

[2] Federal Communication Commission, "Evaluating Compliance with FCC-Specified Guide-lines for Human Exposure to Radio frequency Radiation," OST/OET Bulletin Number 65, August 1997.

[3] Motorola Labs, "Proposed Revision to Recommendation ITU-R P.1411-1: Suburban Multipath Propagation and Path Loss Characteristics in the 3.7 GHz Band", ITU-R WP3K, Geneva, Switzerland, May 2002.