Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*		Nr - *No.*		
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69) EED/N/RN Stefan Zürbes (+49-911-5217 493)				
Dokansv/Godk - *Doc respons/Approved*	Kontr - *Checked*	Datum - *Date*	Rev	File
		1999-05-31	C	

Bluetooth voice and data performance in 802.11 DS WLAN environment

Abstract

In this document, the impact of a 20dBm 802.11 Direct-Sequence WLAN system on a 0dBm Bluetooth link is studied. A typical office environment is assumed with a small number of WLAN access points and a large number of WLAN terminals. The study differentiates between the impact on the Bluetooth data link and the impact on the Bluetooth voice link. Results show that a Bluetooth voice link is disturbed in less than 1% of the cases when the Bluetooth operating distance remains below 2m. If the operating distance increases to 10m, the probability of disturbance increases to 8%. For the Bluetooth data link, a throughput reduction of more than 10% occurs with 24% probability at an operating distance of 10m. Because of the limited frequency overlap of the WLAN and Bluetooth systems, the throughput reduction in the Bluetooth system can never exceed 22%.

1. INTRODUCTION

The Wireless Local Area Network (WLAN) system based on the IEEE 802.11 standard and the short-range radio system based on Bluetooth (BT) share the same ISM band at 2.45 GHz. Bluetooth is typically used for providing device-to-device connectivity on an ad-hoc basis, whereas the WLAN systems target for a wireless replacement of the LAN infrastructure. In an office environment, WLAN and BT radios will typically operate simultaneously. Because they operate in the same radio band, mutual interference is a concern.

In this document, the impact of a WLAN system on the BT performance is investigated. Although the IEEE 802.11 standard allows for different types of modulation (e.g. FH and DS) and data rates, the study is limited to the 802.11 systems based on Direct Sequence Spread Spectrum (DSSS) with the latest modulation scheme (CCK) providing a data rate of 11 Mb/s. The impact of BT on the 802.11 system is not within the scope of this document.

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*		Nr - *No.*		
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69) EED/N/RN Stefan Zürbes (+49-911-5217 493)				
Dokansv/Godk - *Doc respons/Approved*	Kontr - *Checked*	Datum - *Date*	Rev	File
		1999-05-31	C	

2. TOPOLOGY

For the interference studies, a typical office environment is assumed. Figure 1 shows a WLAN system with two access points (AP). WLAN terminals (STA) are uniformly distributed with a density of one STA per 25 m^2. A single AP serves 50 STAs (one AP per 1250 m^2).

The performance of the BT is determined by the intended power received and the interfering power received, or the total C/I. This in turn will depend on

1. The distance between the BT receiver and BT transmitter
2. The distance between the BT receiver and the STA transmitter
3. The distance between the BT receiver and the AP transmitter

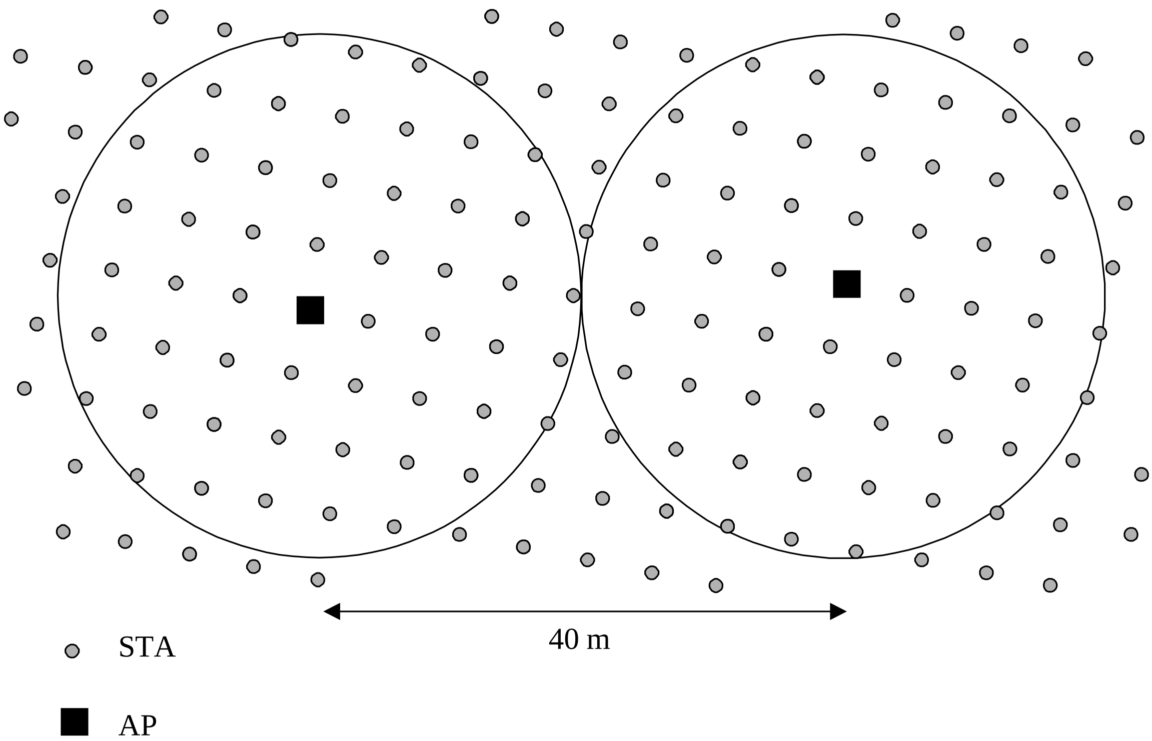

Figure 1. Simulated office environment. The BT receiver can be located on any location between the APs

The C/I will also depend on the transmit powers applied in the AP, STA and BT transmitters. In this document, the AP and STA transmit powers are fixed at +20 dBm whereas the BT transmit power is fixed at 0 dBm.

In the office topology shown, it is assumed that a single BT piconet is associated with each STA. Because of the distance between the STAs and the low BT transmit power, the mutual interference between BT piconets is ignored. Therefore, only the STA and AP interference is taken into account in the evaluation of the BT link. The investigation can be limited to a single BT piconet located at different positions from the APs. In order to avoid border effects, the BT receiver is positioned at an arbitrary point between the two access points, far away from the edges of the area.

3. PROPAGATION MODEL

A simple indoor propagation model has been used [1]: line-of-sight propagation is assumed for the first 8m, thereafter a propagation exponent of 3.3 is assumed. The path loss L_{path} can be expressed as:

$$L_{path} = 20 \log (4\pi r / \lambda) \qquad r \le 8\text{m}$$

$$= 58.3 + 33 \log (r / 8) \qquad r > 8\text{m}$$

where λ is the free-space wavelength at 2.45 GHz (12.24cm) and r is the range in m. Note that wall or floor losses where not included.

4. BLUETOOTH AND WLAN INTERFERENCE MODEL

The WLAN system is an 802.11 DS system with an 11Mb/s instantaneous rate. The assumed timing of the WLAN transmission is shown in Figure 2. Each data packet in one direction is followed by an acknowledgement from the recipient in the opposite direction. The data packet typically lasts 1210µs, the ACK 106µs and there is a 10µs delay between data packet and the ACK. Information is typically streamed in a continuous manner: the next packet arrives 350µs after the end of the previous ACK. The information exchange is asymmetric: either the AP is sending data packets and the STA is sending acknowledgements, or the situation is reversed.

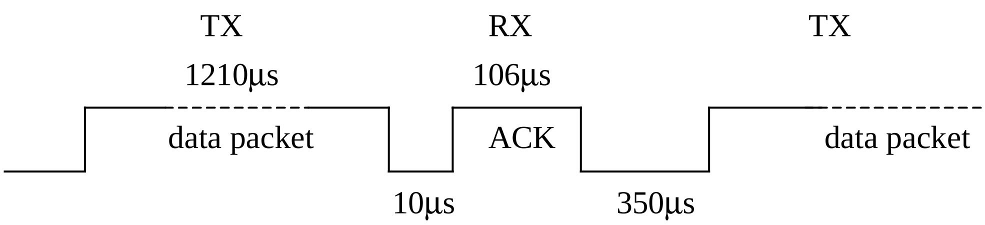

Figure 2. Timing on the WLAN channel.

For the Bluetooth system, both a data and a voice link are investigated. For the data link, the DH1-type was assumed (single-slot packets in both directions providing an overall link load of 366/625 or 58%). The DH1 packet does not contain error protection bits; however, it is the shortest data packet supported. The information exchange is symmetric. For voice, the HV3-type link was assumed (every 6 time slots,

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69)
EED/N/RN Stefan Zürbes (+49-911-5217 493)

Nr - *No.*
Dokansv/Godk - *Doc respons/Approved* | Kontr - *Checked* | Datum - *Date* 1999-05-31 | Rev C | File

a voice packet is transmitted in both directions providing a link load of (2×366)/(6×625) or 20%). The timing for the DH1 and HV3 packets is illustrated in Figures 3 and 4.

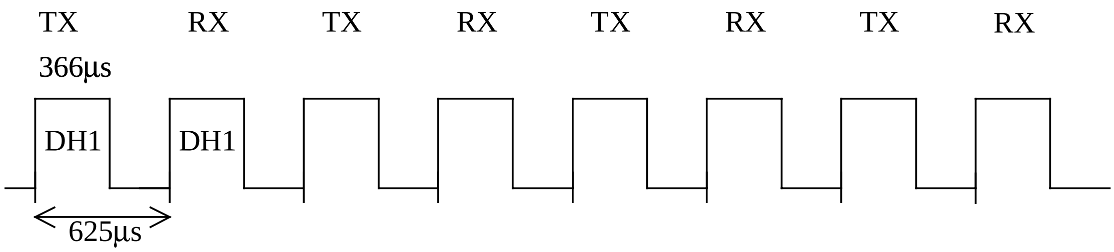

Figure 3. Timing on the BT data link.

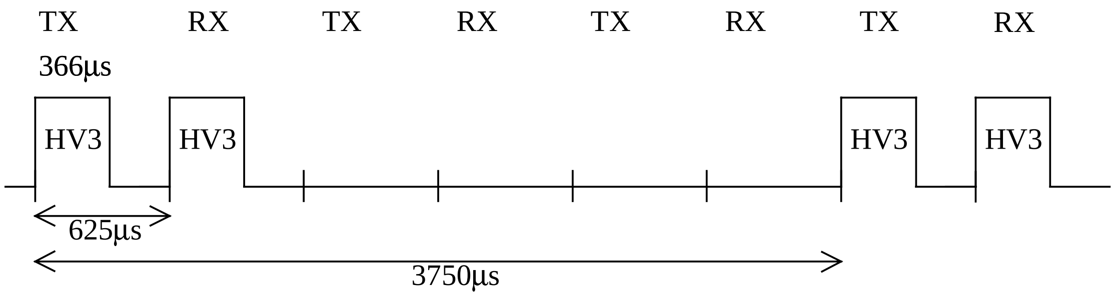

Figure 4. Timing on the BT voice link.

When transmitting, the WLAN system occupies about 17MHz of the 2.45GHz ISM band. The total amount of power transmitted amounts to 20dBm. When the BT receiver hops in the WLAN band, it filters out the BT hop bandwidth. For the BT receiver, the WLAN signal is regarded as white noise. Assuming a 0.85MHz noise bandwidth in the BT receiver, a filter suppression of 13dB is achieved. With a C/N required of 17dB @ 10^{-3} BER, the required C/I towards a WLAN transmitter amounts to 4dB. The Bluetooth system transmits with a 0dBm power level. The –20dB transmit bandwidth is 1MHz.

Note that mutual interference between the WLAN system and the BT system will only occur if the signals of both systems overlap in both frequency and time. The BT connection uses 79 hop channels of 1 MHz; 17 hops out of the 79 will be affected by the WLAN interference. In addition, both the WLAN system and the BT system apply packet transmission and time division duplexing. This means that the transmission is intermittent. Each BT transmission is at a different hop frequency, i.e. it hops at the packet rate.

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69)
EED/N/RN Stefan Zürbes (+49-911-5217 493)

Nr - *No.*
Dokansv/Godk - *Doc respons/Approved* | Kontr - *Checked* | Datum - *Date* 1999-05-31 | Rev C | File

5. RANGE OF INTERFERENCE

For the range of interference, we must distinguish between voice and data performance. The BT data channel applies retransmission and can therefore cope with a higher packet erasure rate (PER) than voice. For the performance thresholds (the thresholds where still acceptable performance is experienced), we take PER=10% for data and PER=1% for voice. These two values must be considered with care since the user experience is largely determined by the time period the interference lasts. For example, a 2% PER for a period of 10 seconds in a voice connection will be more annoying to the user than a 10% PER in a period of 100ms. This aspect will be further elaborated on in section 8.

First, the BT data connection is considered (DH1 packets). Simulations have been carried out using the propagation and timing models as described in sections 3 and 4. Table 1 indicates how close an STA can come to a BT receiver under the conditions of 10% PER in the BT data link. The distance between the BT receiver and transmitter D_{BT} is a variable shown in the first column. Since the activity of the STA depends on whether it transmits data packets or ACKs (see Figure 1), the minimum interfering distances differ for both conditions. The interfering distance (the distance for which the interference starts to have a noticeable impact on the BT link) is smaller when the interferer only transmits ACKs. To the interfering distance D_{STA}, there correspond a number of STA interferers N_{STA} according to the topology shown in Figure 1. This number is also listed in Table 1 and indicates how many STAs can potential interfere with the BT communications for the considered BT operating distance D_{BT}. Since the distance at which the data transmitting WLAN unit starts to interfere is much larger than the distance at which the ACK transmitting WLAN unit starts to interfere, the number $N_{STA,ad}$ in the fifth column represents the number of WLAN units interfering with the BT link irrespective whether they are sending data or ACKs. Table 2 shows the same information with the STA replaced by the AP. Because the STAs and the APs transmit with the same 20dBm power level, the interfering distances D_{STA} and D_{AP} are the same for the same D_{BT}. However, since the density of the APs is much lower, the number N_{AP} of interfering APs is much lower than the number N_{STA} of STAs. Note that non-integer values for the AP numbers are used. The number N_{AP} of interfering APs and the number N_{STA} of interfering STAs is important to determine the impact of the WLAN transmission on the BT link. These numbers will be used in sections 7 and 8.

The same analysis can be carried out for the BT voice connection (HV3 packets). Table 3 indicates how close an STA can come to a BT receiver under the conditions of 1% PER in the BT voice link. Table 4 shows the same information for an AP interfering a voice link.

For the tables, a continuous transmission was assumed for both the BT and the WLAN system. For the 802.11 data, the timing as shown in Figure 2 has been applied. For Bluetooth, the data and voice timing as shown in Figures 3 and 4 have been applied. From the tables, it can be concluded that data (for a 10% packet erasure rate)

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69)
EED/N/RN Stefan Zürbes (+49-911-5217 493)

Nr - *No.*
Dokansv/Godk - *Doc respons/Approved* | Kontr - *Checked* | Datum - *Date* 1999-05-31 | Rev C | File

is more sensitive than voice (for a 1% packet erasure rate). This is because the DH1 payload is protected with a CRC and the packet is rejected when the payload is in error. In the HV3 packet, there is no check on the payload: residual errors in the payload are allowed and handled by the CVSD speech coding. In the HV3 packet, only the access code failure and/or the header failure account for the packet erasure rate.

	STA transmitting data		**STA transmitting ACK**	
D_{BT} **(m)**	$D_{STA,d}$ **(m)**	$N_{STA,d}$	$D_{STA,ad}$ **(m)**	$N_{STA,ad}$
0.5	8.0	8	0.0	1
1.0	12.2	19	0.1	1
2.0	18.5	43	0.2	1
4.0	28.2	100	0.3	1
7.0	39.6	197	0.6	1
10.0	53.7	362	0.9	1

Table 1. STA interfering distance and number of STA interferers for a BT data link.

	AP transmitting data		**AP transmitting ACK**	
D_{BT} **(m)**	$D_{AP,d}$ **(m)**	$N_{AP,d}$	$D_{AP,ad}$ **(m)**	$N_{AP,ad}$
0.5	8.0	0.16	0.0	0.00
1.0	12.2	0.37	0.1	0.00
2.0	18.5	0.86	0.2	0.00
4.0	28.2	2.00	0.3	0.00
7.0	39.6	3.94	0.6	0.00
10.0	53.7	7.24	0.9	0.00

Table 2. AP interfering distance and number of AP interferers for a BT data link.

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69)
EED/N/RN Stefan Zürbes (+49-911-5217 493)
Nr - *No.*
Dokansv/Godk - *Doc respons/Approved* | Kontr - *Checked* | Datum - *Date* 1999-05-31 | Rev C | File

	STA transmitting data		**STA transmitting ACK**	
D_{BT} **(m)**	$D_{STA,d}$ **(m)**	$N_{STA,d}$	$D_{STA,ad}$ **(m)**	$N_{STA,ad}$
0.5	4.0	2	2.0	1
1.0	8.0	8	4.0	2
2.0	12.2	19	8.0	8
4.0	18.5	43	12.2	19
7.0	26.0	85	17.1	37
10.0	35.3	156	23.2	67

Table 3. STA interfering distance and number of STA interferers for a BT voice link.

	AP transmitting data		**AP transmitting ACK**	
D_{BT} **(m)**	$D_{AP,d}$ **(m)**	$N_{AP,d}$	$D_{AP,ad}$ **(m)**	$N_{AP,ad}$
0.5	4.0	0.04	2.0	0.01
1.0	8.0	0.16	4.0	0.04
2.0	12.2	0.37	8.0	0.16
4.0	18.5	0.86	12.2	0.37
7.0	26.0	1.70	17.1	0.73
10.0	35.3	3.13	23.2	1.35

Table 4. AP interfering distance and number of AP interferers for a BT voice link.

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69)
EED/N/RN Stefan Zürbes (+49-911-5217 493)

Nr - *No.*

Dokansv/Godk - *Doc respons/Approved* | Kontr - *Checked* | Datum - *Date* 1999-05-31 | Rev C | File

6. THE 802.11 TRAFFIC MODEL

The BT performance is determined by the activity factors of the AP and the STA. Since the AP serves 50 STAs, the activity factor of the AP will be a least 50 times the STA activity factor. In practice this number is much higher since downlink traffic (flowing from AP to STA) dominates.

Table 5 shows the traffic typically expected from AP to STA and vice versa. The number # indicates how many of such transactions are carried out during an eight-hour working day. The block time corresponds to the time the channel is completely occupied as a result of the transaction. For the block time, an efficiency of 37% (4/11) was assumed. This includes the overhead presented by headers, guard times and ACK transmissions. From Table 5, it can be concluded that the load in the downlink (from AP to 50 STAs) is merely 3%, whereas the load in a single uplink (from a single STA to the AP) is 0.02%. As mentioned before, downlink traffic apparently dominates.

	From AP to STA			**From STA to AP**		
transaction	**#**	**size (Bytes)**	**block time (ms)**	**#**	**size (Bytes)**	**block time (ms)**
Email	20	10K	20	10	10k	20
Email / attach	5	200K	400	2	200k	400
File	10	200K	400	10	200k	400
Internet	1k	5K	10			

Table 5. Traffic intensity of a WLAN system.

7. BLUETOOTH DATA PERFORMANCE

When a WLAN DS 802.11 system co-exists with a BT system, the two systems overlap in 17 hop channels of the BT system. The BT systems uses 79 channel in total. The worst case throughput reduction amounts to 17/79 or 22%. However, in practice, the reduction is much less because of interference topology and traffic conditions.

In this section, it is determined with which probability the BT data link throughput is reduced with more than 10%. Note that in the whole considerations, reverse link failures are not considered; this can be motivated by the ACKs being

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69)
EED/N/RN Stefan Zürbes (+49-911-5217 493)

protected by a 1/3 rate FEC coding. The following formula is used:

$$P\{PER>10\%\} = 1 - (1 - p_{AP,ad})^{N_{AP,ad}} * (1 - p_{AP,d})^{(N_{AP,d} - N_{AP,ad})} * (1 - p_{STA,ad})^{N_{STA,ad}} * (1 - p_{STA,d})^{(N_{STA,d} - N_{STA,ad})} \quad (1)$$

where

$p_{AP,d}$ is the probability that an AP is transmitting data

$p_{AP,ad}$ is the probability that an AP is transmitting data or ACKs

$p_{STA,d}$ is the probability that a STA is transmitting data

$p_{STA,ad}$ is the probability that a STA is transmitting data or ACKs

In using this Equation 1, it is assumed that the probabilities p_{AP}, p_{STA} are small and conditional probabilities can be neglected. The number $N_{STA,ad}$ represents the number of STAs within a circle with radius $D_{STA,ad}$ in which both data and ACK transmitting STAs are potential interferers. The number ($N_{STA,d}$ - $N_{STA,ad}$) represents the number of STAs within a ring with inner radius $D_{STA,ad}$ and outer radius $D_{STA,d}$ in which only data transmitting STAs are potential interferers. The same argumentation can be given for the numbers $N_{AP,ad}$ and ($N_{AP,d}$ - $N_{AP,ad}$).

For the determination of the probability of uplink and downlink traffic, we consider Table 5:

P_{DL} = 0.056944%

P_{UL} = 0.017361%

Hence the probability that a STA is transmitting data at an arbitrary time is:

$p_{STA,d} = p_{UL}$ = 0.017361%

and the probability that an STA is transmitting data or ACKs is

$p_{STA,ad} = p_{UL} + p_{DL}$ = 0.074305%

The probability that an AP is transmitting data to any of the 50 STAs at an arbitrary time is approximately (for small p_{DL}):

$p_{AP,d}$ = 50 * p_{DL} = 2.85%

and the probability that an AP is transmitting data or ACKs is approximately (for small p_{DL} and p_{UL}):

$p_{AP,ad}$ = 50 * (p_{UL} + p_{DL}) = 3.72%

Using these probabilities p_{STA} and p_{AP} and the values of N_{STA} given in Table 1, the probabilities that a data link is disturbed (PER>10%) as a function of the BT distance

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*		Nr - *No.*		
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69) EED/N/RN Stefan Zürbes (+49-911-5217 493)				
Dokansv/Godk - *Doc respons/Approved*	Kontr - *Checked*	Datum - *Date*	Rev	File
		1999-05-31	C	

D_{BT} and whether the BT receiver is in interference range of an AP are summarized in Table 6.

D_{BT} (m)	$N_{AP,ad} = 0$ $N_{AP,d} = 0$	$N_{AP,ad} = 0$ $N_{AP,d} = 1$	$N_{AP,ad} = 1$ $N_{AP,d} = 0$	$N_{AP,ad} = 1$ $N_{AP,d} = 1$	$N_{AP,ad} = 2$ $N_{AP,d} = 0$
0.5	0.002	0.030	0.039	0.066	0.075
1.0	0.004	0.032	0.041	0.068	0.077
2.0	0.008	0.036	0.045	0.072	0.080
4.0	0.018	0.046	0.054	0.081	0.089
7.0	0.034	0.062	0.070	0.097	0.105
10.0	0.061	0.088	0.096	0.122	0.130

Table 6. Probability of interference on BT data link as a function of the BT distance for different AP presence.

In Table 6, only the areas in proximity of the AP were used (N_{AP} was 0, 1, or 2). For N_{STA}, the values as found in Table 1 were used. When the entire area is considered, the N_{AP} values as found in Table 2 should be used in Equation 1. The final result, that is the probability that a data link is disturbed considering the entire area, is summarized in Table 7.

D_{BT} (m)	P{PER>10%}
0.5	0.007
1.0	0.015
2.0	0.032
4.0	0.073
7.0	0.138
10.0	0.239

Table 7. Probability of interference on BT data link as a function of the BT distance.

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*		Nr - *No.*		
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69) EED/N/RN Stefan Zürbes (+49-911-5217 493)				
Dokansv/Godk - *Doc respons/Approved*	Kontr - *Checked*	Datum - *Date*	Rev	File
		1999-05-31	C	

8. BLUETOOTH VOICE PERFORMANCE

In this section, it is determined with which probability the BT voice link is significantly degraded. We assume that a 1% PER gives still acceptable voice quality. For the determination of the probability of uplink and downlink traffic, we have ignored the short transactions (i.e. the transactions with block times of less than 50 ms). These short bursts of interference on the voice link will not be perceived by the listener (note that in 50ms, there are 7 voice packets sent at 7 different hop frequencies which are spread out in the 80 MHz). Regarding the traffic model summarized in Table 5, the Emails without attachments and the Internet pages are not included in the interference scenario for voice. Taking these considerations into account, the probability for uplink and downlink transmission is:

P_{DL} = 0.020833%

P_{UL} = 0.016667%

Hence the probability that a STA is transmitting data at an arbitrary time is:

$p_{STA,d} = p_{UL}$ = 0.016667%

and the probability that an STA is transmitting data or ACKs is

$p_{STA,ad} = p_{UL} + p_{DL}$ = 0.0375%

The probability that an AP is transmitting data to any of the 50 STAs at an arbitrary time is approximately (for small p_{DL}):

$p_{AP,d} = 50 * p_{DL}$ = 1.04%

and the probability that an AP is transmitting data or ACKs is approximately (for small p_{DL} and p_{UL}):

$p_{AP,ad} = 50 * (p_{UL} + p_{DL})$ = 1.875%

Using these probabilities p_{STA} and p_{AP} and the values of N_{STA} given in Table 3, the probabilities that a voice link is disturbed (PER>1%) as a function of the BT distance D_{BT} and whether the BT receiver is in interference range of an AP are summarized in Table 8.

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*		Nr - *No.*		
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69) EED/N/RN Stefan Zürbes (+49-911-5217 493)				
Dokansv/Godk - *Doc respons/Approved*	Kontr - *Checked*	Datum - *Date*	Rev	File
		1999-05-31	C	

D_{BT} (m)	$N_{AP,ad} = 0$ $N_{AP,d} = 0$	$N_{AP,ad} = 0$ $N_{AP,d} = 1$	$N_{AP,ad} = 1$ $N_{AP,d} = 0$	$N_{AP,ad} = 1$ $N_{AP,d} = 1$	$N_{AP,ad} = 2$ $N_{AP,d} = 0$
0.5	0.001	0.011	0.019	0.029	0.038
1.0	0.002	0.012	0.020	0.031	0.039
2.0	0.005	0.015	0.023	0.034	0.042
4.0	0.011	0.021	0.030	0.040	0.048
7.0	0.022	0.032	0.040	0.050	0.058
10.0	0.039	0.049	0.057	0.067	0.075

Table 8. Probability of interference on BT voice link as a function of the BT distance for different AP presence.

In Table 8, only the areas in proximity of the AP were used (N_{AP} was 0, 1, or 2). For N_{STA}, the values as found in Table 3 were used. When the entire area is considered, the N_{AP} values as found in Table 4 should be used in Equation 1. The final result, that is the probability that a voice link is disturbed considering the entire area, is summarized in Table 9.

D_{BT} (m)	P{PER>1%}
0.5	0.001
1.0	0.004
2.0	0.010
4.0	0.023
7.0	0.045
10.0	0.081

Table 9. Probability of interference on BT voice

Uppgjord (även faktaansvarig om annan) - *Prepared (also subject responsible if other)*		Nr - *No.*		
ERH/T/B Jaap C. Haartsen (+31- 592 - 63 74 69) EED/N/RN Stefan Zürbes (+49-911-5217 493)				
Dokansv/Godk - *Doc respons/Approved*	Kontr - *Checked*	Datum - *Date* 1999-05-31	Rev C	File

link as a function of the BT distance.

9. CONCLUSIONS

In this document, simulation results are shown for Bluetooth data and voice connections in the presence of an interfering 802.11 DS WLAN system. The WLAN access points and terminals operate with a 20 dBm transmit power; the Bluetooth devices operate with a 0 dBm transmit power.

Under normal traffic conditions in the WLAN, the Bluetooth voice user is not affected as long as his operating distance remains below 2m. If the operating distance increases to 10m, the probability that there is a noticeable interference on the link increases to 8%. The Bluetooth data link allows and experiences more degradation. A throughput reduction of more than 10% occurs with 24% probability at an operating distance of 10m. However, because of the limited frequency overlap of the WLAN and Bluetooth systems, the throughput reduction in the Bluetooth system can never exceed 22%.

REFERENCES

[1] A. Kamerman, “Coexistence between Bluetooth and IEEE 802.11 CCK solutions to avoid mutual interference,”*Lucent Technologies Bell Laboratories*, Jan 1999.