Canute

FCC Submission for 2.4 GHz FHSS Operation

S.J. Dickinson and I.G. Knowles

Project Canute

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Tality UK Ltd.
The Alba Campus, Livingston, West Lothian, EH54 7HH, Scotland
Tel: +44 1506 595000
Fax: +44 1506 595959

AMENDMENT HISTORY

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0.5	15/03/01	IGK	Revised for project Fonseca.
1.0	23/03/01	IGK	Revised after review
2.0	24/01/02	SDM	Updated to reflect the changes for Canute
2.1	14/08/02	SDM	Updated to reflect the change in channel update timing.

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DEFINITIONS, ACRONYMS AND ABBREVIATIONS

2G4	The 2.4GHz ISM band. Used as shorthand for the 2.4GHz stack under discussion.
Channel collision	The simultaneous occupancy of a hopping channel by multiple transmitters.
DECT	Digital Enhanced Cordless Telecommunications.
EIRP	Equivalent isotropically Radiated Power.
ETSI	European Telecommunications Standards Institute.
FCC	Federal Communications commission (the body in the USA that regulates the use of the radio spectrum).
FH	Frequency Hopper: the name of the software component responsible for frequency hopping.
FHSS	Frequency Hopping Spread Spectrum.
FP	Fixed Part or base station.
Hand-over	A process by which a second traffic bearer is established to carry an existing call. Once established the first traffic bearer can be released.
HSI	Hop Sequence Index; used to index into the pattern table.
ISM	Industrial, Scientific, Medical band: a radio frequency band in the range 2400 – 2483.5 MHz
LCG	Linear Congruence Generator: a type of random number generator
LDC	Low Duty Cycle: a power saving feature.
OET	Office of Engineering and Technology, a division of the FCC.
PP	Portable Part or handset.
PSCN	Primary Scan carrier Number; used in DECT.
PSPN	Primary Scan Pattern Number; the analogue of the PSCN for frequency hopping.
Radio Cell	The area covered by a single FP.
RFPI	Radio Fixed Part Identity
RNG	Random Number Generator; more accurately a Pseudo-Random Number Generator or PRNG.
RSSI	Received Signal Strength Indication.
Sequence collision	When two transmitters, with overlapping radio cells, are using the same slot, pattern and phase within the pattern. Channel collisions will occur on every frame, until the slot, pattern or phase is changed.
TDD	Time Division Duplex.
TDMA	Time Division Multiple Access.
WDCT	Worldwide Digital Cordless Telecommunications; Siemens' proprietary protocol based on DECT that uses the 2.4 GHz band.

1 INTRODUCTION

In the US the 2400 – 2483.5 MHz band (henceforth the 2.4 GHz band) is subject to FCC regulations, in particular Part 15 Section 247.

Tality UK Limited has developed a protocol stack for a cordless telephone product that uses the 2.4 GHz band. This system is referred to here by as the ‘2G4 stack’. This protocol stack is based on a DECT standard protocol stack that has been modified to use frequency hopping spread spectrum techniques in order to meet the FCC requirements.

1.1 Scope

This document describes the salient features of the 2G4 protocol stack as they relate to the FCC requirements for using the 2.4 GHz band.

2 BRIEF SYSTEM DESCRIPTION

The basic system is a cordless telephone system, based on DECT. Because DECT is such a fundamental part of the proposed system, a brief description of this is given first.

DECT is a low-power two-way digital wireless communications system. Whilst DECT is a general digital communications system, it is most commonly used for cordless telephone systems. In particular it is used for residential telephone systems.

DECT uses TDMA to provide two-way communication between a base-station and multiple handsets. In this document the base-station is referred to as the Fixed Part (FP) and the handset is referred to as the Portable Part (PP).

Unlike a DECT system, the 2G4 system does not have exclusive use of the spectrum. It has to share the spectrum with other users. The 2G4 system uses frequency hopping to share the spectrum with other users according to the requirements specified by the FCC.

It is the frequency hopping requirement that creates the biggest difference between a DECT and a 2G4 system. The other main difference between the two systems is the TDMA frame structure – 2G4 has to use fewer ‘slots’ in the frame due to a lower bit rate.

2.1 Frequency channels

The 2G4 stack uses carriers whose centre frequencies are given by the following formula[1]:

$$f_n = (2401.280 + n \times 1.024)\ \text{MHz} \qquad n = 0,\ldots,78$$

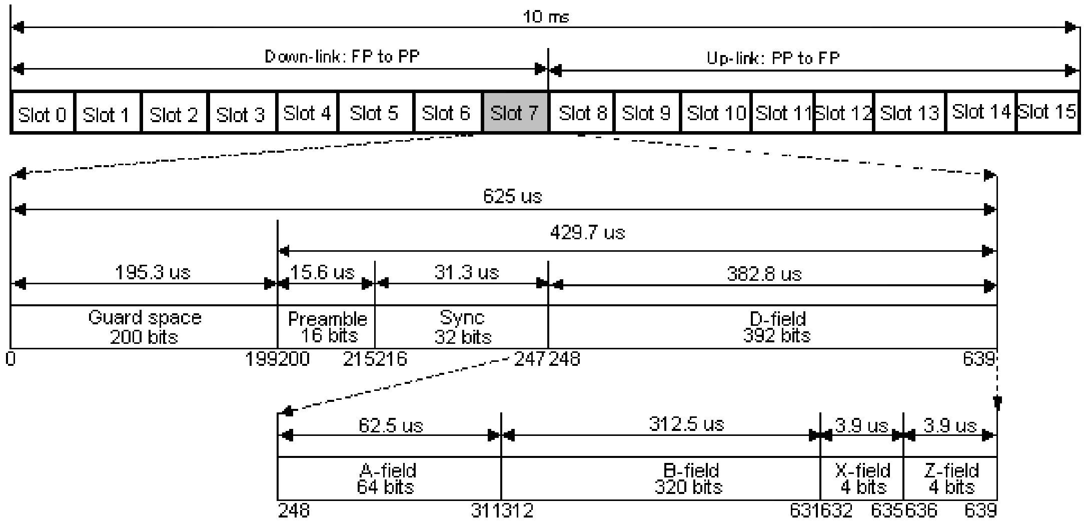
This gives 79 channels, with equal spacing of 1024 kHz, lying between 2401.280 and 2481.152 MHz. These channel frequencies conform to the constraints of the ISM band.

A full listing of the channel frequencies is given in Appendix A.

[1] These numbers are appropriate to the current 2G4 system and RF module; future implementations may use a different number of channels and centre frequencies.

2.2 TDMA frames structure

The TDMA frame structure in use is shown below:



The basic, repeating, frame structure is 10 ms long. It is sub-divided into 16 slots, each 625 µs long. The active transmission time is 429.7 µs. The first 8 slots form the 'down-link', when the FP transmits to the PPs. The last 8 slots form the 'up-link', when the PPs transmit to the FP.

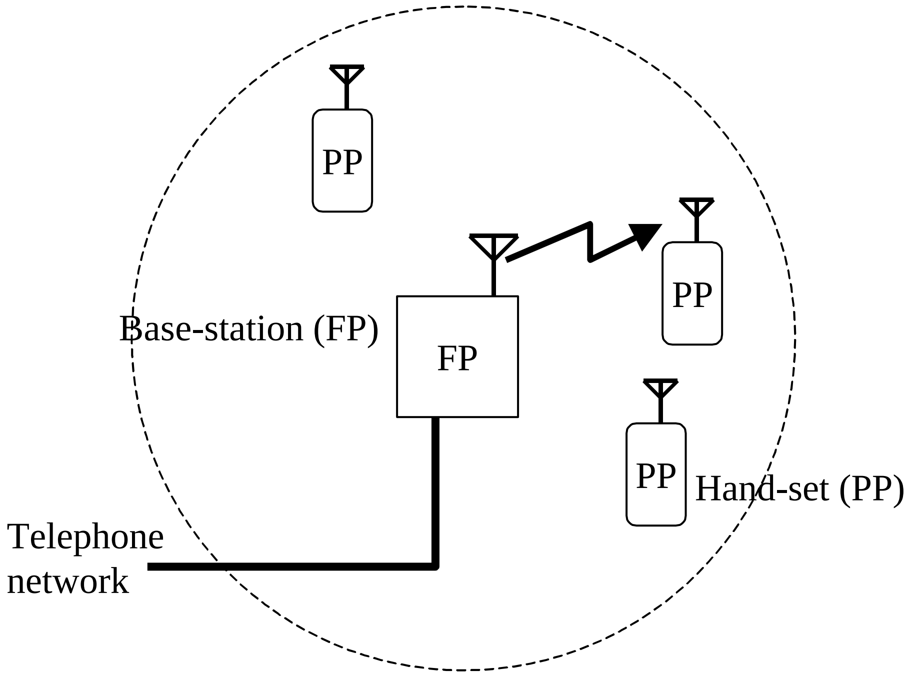
The 2G4 stack uses TDD to carry a two-way voice communication. This is always by using slot-pairs: 0 and 8, 1 and 9, 2 and 10, 3 and 11, 4 and 12, 5 and 13, 6 and 14, 7 and 15. In this way the up-link transmission of the duplex communication is always 5ms after the corresponding downlink transmission.

There is only one transceiver in a FP or PP therefore in any single slot, the FP or PP can only ever be receiving or transmitting.

2.3 Residential / domestic system

A residential or domestic system is for use in the home. A single FP is used with multiple PPs. There can be any number of PPs, although only 4 simultaneous duplex connections to the FP are allowed. This is because the system is capable of running any or all connections in a dual-bearer mode (see section 3.10), each of which requires two slot pairs. Therefore, four such connections is the limit due to the number of slot-pairs in the TDMA frame structure.

The figure illustrates the basic system configuration.



2.4 Bearers

An important concept in DECT and the 2G4 stack is the notion of a bearer. A bearer is the medium used for carrying a communication.

In a DECT system a bearer is defined by a combination of channel number and slot number. However, because 2G4 is a frequency hopping system, a bearer is defined by a hopping sequence and slot number.

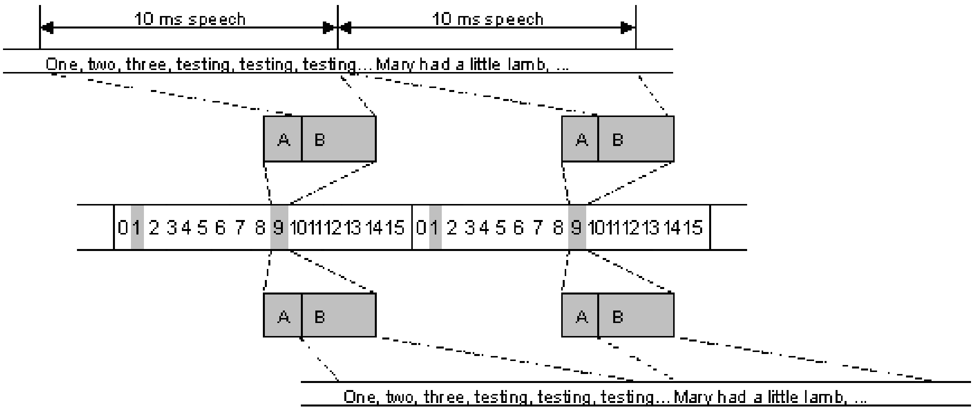
There are two types of bearer in the 2G4 system:

1. Dummy bearer
   - This is used to carry a 'beacon' and other broadcast information.
   - The FP will broadcast a dummy bearer all the time it is powered up and operating.
   - Only the FP transmits a dummy bearer.
   - As it is a simplex transmission, only a downlink slot is used.
   - The broadcast information is contained in the 'A-field' section of the transmission (the 'B-field' section is not required, and is therefore not transmitted).
2. Traffic bearer
   - This is used to carry a voice call.
   - As it is a duplex transmission both a downlink and up-link slot are used. The slots used are always a slot-pair.
   - The 'A-field' section contains the same information as the dummy bearer, with the addition of extra signalling required for the call. The voice data is contained in the 'B-field' section.

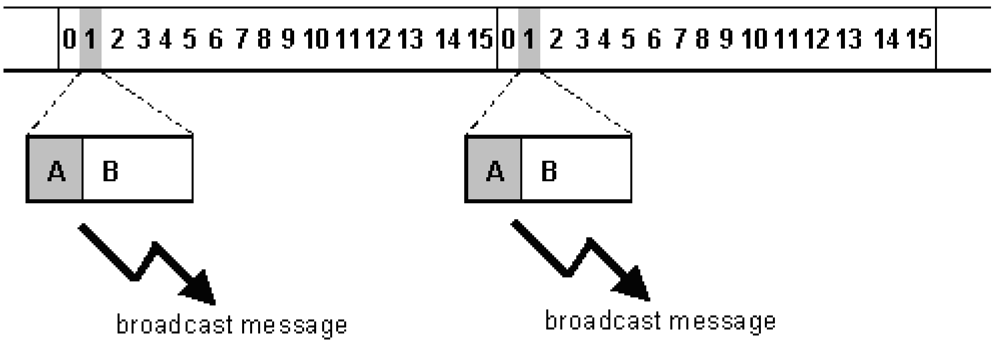
In the 2G4 system the dummy bearer is usually separate from the traffic bearers, i.e. they are on different slots. In the case that 8 simultaneous traffic bearers are required (the maximum number that can be supported by the FP) then one of the traffic bearers will also take over the responsibilities of the dummy bearer. In the remainder of the document this shall be referred to as a 'combined dummy/traffic bearer'.

Since the traffic bearer is already carrying the same information as the dummy bearer, the 'combined dummy/traffic bearer' is the same length as a normal traffic bearer. However, the combined dummy/traffic bearer has some restrictions (compared to a normal traffic bearer) with regards to frequency hopping as detailed later.

The following diagram shows the up-link transmission of a traffic bearer; the downlink transmission is in slot 1.



The following diagram shows a dummy bearer transmission. Note, that it uses only a downlink slot and the A-field of the packet.



3 OVERVIEW OF FREQUENCY HOPPING ALGORITHM

3.1 Hopping rate

Each bearer will change frequency channel, or hop, once per frame, *i.e.* the bearer hopping rate is 100 hops/second. The change occurs in the middle of the frame, between the down-link and the up-link.

In the case of a traffic bearer this means that the down-link of any given frame will use the same frequency channel as the up-link of the previous frame.

The maximum hop rate occurs in the case where all slots are active, which occurs when there are 8 active traffic bearers. In this case, there will be 1600 frequency changes/second, since each slot will hop independently at a rate of 100 hops/second. However, because the down-link and the preceding up-link in any slot-pair use the same channel, this is only actually 800 channels/second.

3.2 Hopping Sequence

There are two possible methods for generating the hopping sequences: tables and random number generators (RNGs). Tables are hand-crafted to have specific properties and reverse table-lookup can be used to deduce the position in the table. RNGs generate very long period sequences that are less prone to 'sequence collision'. The current implementation of the 2G4 stack uses only the table-based solution.

3.2.1 Hopping pattern base table

A dummy bearer or combined dummy/traffic bearer uses a table-generated hop sequence.

A single base table is constructed containing a permutation of the channel numbers 0, 1, 2,…,74 (there are no repeats in the sequence). An extract is shown in the following table where 'i' is the index, and 'F_0' is the base table sequence.

i	$F_0(i)$
0	0
1	27
2	38
3	14
…	…
74	44

From this one base table, additional sequences are generated using the formula:

$$F_x(i) = F_0(i) + x \pmod{75}$$

The sequence index 'i' in the above formula is incremented, modulo 75, each frame. The value 'x' is used to select the required pattern. Due to the modulus there are 75 unique patterns permuted from this single base table.

The following table shows an extract of the first 4 patterns.

i	**$F_0(i)$ (Pattern 0)**	**$F_1(i)$ (Pattern 1)**	**$F_2(i)$ (Pattern 2)**	**$F_3(i)$ (Pattern 3)**
0	0	1	2	3
1	27	28	29	30
2	38	39	40	41
3	14	15	16	17
…	…	…	…	…
8	73	74	0	1
…	…	…	…	…
74	44	45	46	47

The base table, is hand-crafted to meet the following criteria:

1. Pseudo-random.
2. When any pattern is time-shifted with respect to any other pattern, the number of direct and adjacent channel collisions is minimised. In this context, because of the expected RF performance, adjacent should be taken to mean within 3 channels or less.
3. When any pattern is time-shifted with respect to any other pattern, the number of direct or adjacent channel collisions on consecutive hops is minimised. Collisions are minimised for 2, 3 and 4 (or more) consecutive hops.
4. Successive channels in the sequence are separated sufficiently to avoid microwave oven interference. In this context, a minimum channel separation of 6 or 8 MHz should be considered sufficient.

The full base table is shown in Appendix B.

3.2.2 LCG random number generator

Traffic bearers can use a pseudo-random number generated hop sequence. The random number generator (RNG) is a Linear Congruence Generator (LCG). The general form of an LCG is:

$$R_{n+1} = a \times R_n + c \pmod m$$

A channel number in the range 0…74 is obtained by applying:

$$\text{Channel number} = (75 \times R_n) / m$$

In the above formula integer division is used. A particular LCG is denoted by LCG(m, a, c, R_0). In the 2G4 stack under consideration, pseudo-random patterns are not used, and therefore they shall not be considered further.

3.2.3 Logical and physical channel numbers

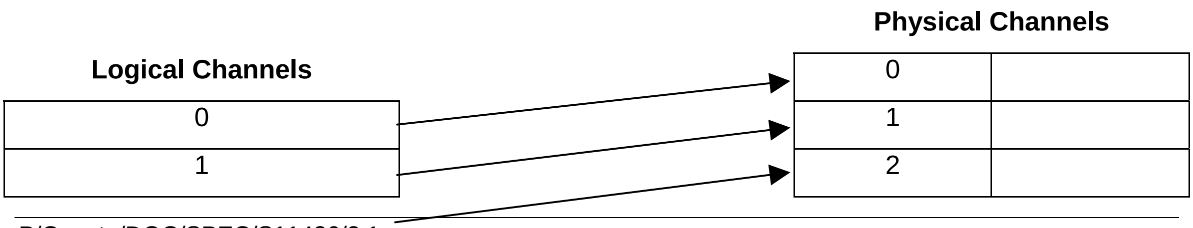
The techniques described so far generate channel numbers in the range 0…74. The 2G4 system can use a total of 79 channels. This results in 4 channels that are not part of the normal sequence and these are reserved as ‘spare channels’.

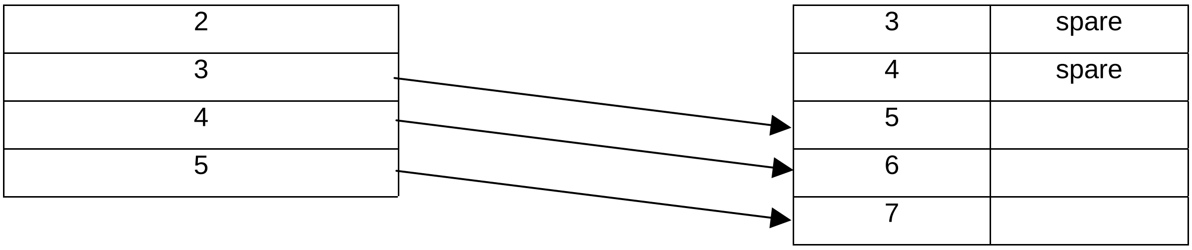
The spare channels are used to adapt the hop sequence, which is a method used by the 2G4 stack to avoid noisy frequency channels (see later).

A mapping table is used to convert the ‘logical channel number’ given by the hopping sequence to the ‘physical channel number’ that is actually used.

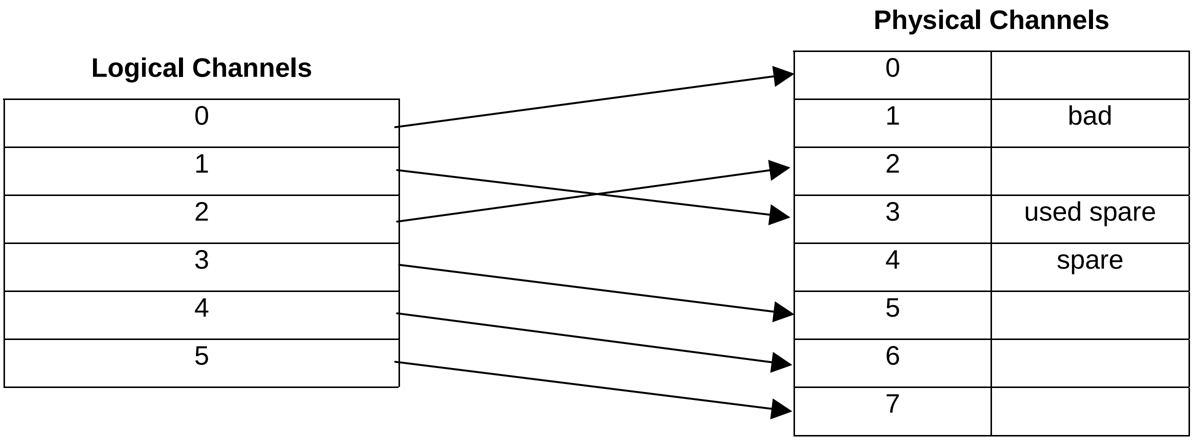
An important feature of the mapping table is that it is always a one-to-one mapping, *i.e.* a physical channel is only ever ‘mapped-onto’ by one logical channel. In this way the channel usage characteristics of the hop sequence are preserved.

For example, consider the following scenario for a small number of logical and physical channels:





Noisy channels can be adapted out of the sequence by 'channel swapping', *i.e.* swapping a good spare channel for a noisy channel. For example, swapping physical channels 1 and 3 gives:



Obviously, the above mapping table is an example. The actual mapping table is shown in Appendix D. It satisfies the following criteria:

1. It maps the 75 logical channels onto 79 physical channels, with a one-to-one mapping. This leaves 4 spare channels that are not used in the unadapted hopping sequence.
2. The spare channels are initially positioned around the 2.45 GHz area. The reason for this is that interference from microwave ovens is likely to be centred on 2.45 GHz.

To facilitate robust 'sequence adaptation' a requirement is that the basic underlying pattern should be changed as little as possible. This is achieved by always ensuring that the channels are swapped back to their original positions when the channel stops being noisy.

3.3 Identifying channel interference

Both the FP and PP can determine channel interference. Interference can be determined by:

1. CRC errors on received packets.
2. RSSI measurements.

Due to other users of the 2.4 GHz band the stack has to be tolerant to some interference. The 2G4 system will not be able to avoid the 'random interference' produced by other frequency hopping systems such as Bluetooth or even other systems similar to itself. However, it is possible to avoid 'relatively static interference' such as that caused by residential microwave ovens.

In order to distinguish between 'random interference' and 'relatively static interference' it is necessary to detect several successive CRC errors or take several RSSI measurements on a suspect channel. Only then is a channel flagged as being 'bad' – and therefore a candidate for adapting out of the sequence.

3.4 Hop sequence adaptation

The hopping sequence will be adapted by channel swapping as described already in section 3.2.3.

In this system, there are only 4 spare channels. Therefore, a maximum of 4 channels can be adapted at any one time.

Only traffic bearers and combined dummy/traffic bearers will have their hop sequence adapted.

The FP decides which channels to swap based on information obtained about channel interference (see section 3.3). The FP will send a message to the PP to indicate the swapped channels. When the PP has acknowledged the message both the FP and the PP will adapt their mapping tables and hence their hopping sequences.

3.5 Starting a dummy bearer

As already mentioned, a FP will broadcast a dummy bearer all the time it is powered up and operating.

When creating a dummy bearer, the FP will select a slot and initial pattern at random.

In addition the FP will select an initial 'hop sequence index' (HSI) at random. The HSI indexes into the base table to select a logical channel. The HSI is incremented (modulo 75) each frame thereafter.

Once the slot, pattern and initial HSI are selected, a sequence of logical channels can be produced at the bearer hopping rate *i.e.* one hop *per* frame or 100 hops/sec.

The randomising of slot, pattern and HSI helps to spread out the use of hopping sequences amongst different FPs. However, because each FP will select their own slot, pattern and HSI independently there will be the occasional 'sequence collision'.

3.5.1 Avoiding dummy bearer 'sequence collision'

Prior to starting a dummy bearer the FP takes RSSI measurements using the proposed slot and pattern. If these indicate no sequence collision then the dummy bearer is started on the proposed slot and pattern combination. No further action is taken to detect (or correct for) sequence collision.

3.6 Gaining sync with a dummy bearer

A PP needs to gain sync with a FP's dummy bearer. This involves:

a) Synchronising in time, to align the TDMA frame structure.

b) 'Locking-on' to the dummy bearer hopping sequence.

In order to align the TDMA frame structure the PP selects an initial channel to start searching. It then waits on that channel until a valid packet is received; this requires the hard-ware to lock onto the 'sync-field' at the start of the packet, which results in the TDMA frame structure being aligned. If a valid packet is not received in a certain time period then the PP will move to another channel and repeat the process.

The most frequently broadcast message on the dummy bearer is the N_T message; is transmitted slightly less than every other frame. This message is used to convey the information required for a PP to 'lock-onto' a FP's dummy bearer.

When an N_T message is received the PP checks the contents to see if it is from a dummy bearer. If it is then the PP can determine the dummy bearer pattern and the HSI (see section 3.6.1).

Searching continues, with the PP changing slot and/or channel until it receives an N_T message that it is able to use to 'lock-onto' an FP's dummy bearer.

3.6.1 Determining the pattern and HSI from an N_T message

A dummy bearer hop sequence is table-generated. The sequence is 75 hops long. Knowing only the pattern number, which is encoded in the N_T message, and the channel number that the N_T message was received on, then the HSI can be found directly by reverse table-lookup. Only channels that are in the unadapted sequence are checked, as a PP can not deduce the HSI on an adapted channel.

Once the pattern number and HSI are determined the PP is able to follow the FP's dummy bearer and it is said to be 'locked-onto' the FP.

3.7 Following a dummy bearer

Once the PP has locked-onto a FP's dummy bearer it follows the dummy bearer hop sequence and receives broadcast messages from the FP. During this process it collects system information broadcast by the FP, including the dummy bearer slot number and PSPN (see later).

Any number of PPs can be locked-onto a particular FP's dummy bearer.

A PP can enter into Low Duty Cycle (LDC) mode. In this mode the PP saves battery power by only receiving dummy bearer transmissions every 16 or 64 frames. This is sufficiently frequent for the PP to stay synchronised and to pick up 'paging messages' that contain information on incoming calls.

Any change to the dummy bearer pattern or slot position has to be broadcast over 64 frames in advance (640ms) so that any PPs that are in LDC mode can follow the dummy bearer to its new pattern or slot.

3.8 Starting a traffic bearer

In DECT and 2G4 it is the PP that initiates the establishment of a traffic bearer. The PP does this by transmitting an ACCESS_REQUEST message to the FP. The FP listens for ACCESS_REQUESTs from PPs on all spare up-link slots, *i.e.*, up-link slots that are not already being used for other traffic bearers.

Successive attempts to establish a traffic bearer use different patterns. This is achieved by the use of the Primary Scan Pattern Number (PSPN). The PSPN determines which pattern is used for a traffic bearer started in the current frame. The FP listens for ACCESS_REQUESTs on the channel determined by the PSPN pattern and its HSI.

The PSPN is incremented (modulo 75) in each frame whilst the FP is powered up and operating.

The PSPN is known to the PP because it is periodically transmitted on the dummy bearer. Thus once a system's PSPN is known and a FP's HSI is determined, the PP can determine what channel the FP will be listening to during its spare up-link slots.

The PP will select a pattern and slot to use and when the PSPN indicates the selected pattern, the ACCESS_REQUEST is transmitted on the appropriate channel and slot. To avoid a long latency whilst the selected pattern 'comes around' on the PSPN, the PP selects a pattern that will occur in N frames time. Where N is both small and determined randomly so as to avoid multiple PPs continually colliding whilst trying to establish traffic bearers.

The ACCESS_REQUEST message contains the identity of the FP to indicate which FP the message is directed at. The requested FP must respond in the next half-frame either with a WAIT or with a BEARER_CONFIRM or with a RELEASE.

Note that the current 2G4 system will always use the even-numbered slot pairs (0&8, 2&10, 4&12 and 6&14) for new traffic bearers, reserving the odd-numbered slot pairs for use with dual-bearer mode (see section 3.10).

3.8.1 Avoiding traffic bearer 'sequence collision'

Prior to starting a traffic bearer RSSI measurements are taken using the proposed slot and pattern. If these indicate no sequence collision then the traffic bearer is started on the proposed slot and pattern combination. No further action is taken to detect (or correct for) sequence collision.

3.9 Starting a combined dummy/traffic bearer

The PP may require to establish a traffic bearer on the slot currently carrying the dummy bearer, usually only when it is the last slot available to it. Due to the need to broadcast any change to the dummy bearer pattern in advance, the PP must use the same pattern that the dummy bearer is currently using.

If the PP has to wait for the dummy bearer pattern to 'come around' on the PSPN this might introduce a long latency. To avoid this the FP always listens to the channel dictated by the dummy bearer pattern on the slot that is the pair of the dummy bearer transmission.

3.9.1 Avoiding combined dummy/traffic bearer 'sequence collision'

No action is taken to avoid sequence collision.

3.10 Dual-bearer mode

The 2.4 GHz band is prone to interference. In order to improve the robustness of the 2G4 system it has the option to operate in a 'dual-bearer mode', whereby two traffic bearers are used simultaneously to carry the same voice data. This achieved by operating in a state of permanent 'bearer hand-over'.

To do this the PP establishes a second traffic bearer with the FP, in the manner already described, except in terms of slot and pattern selection. The two slot pairs in use for a dual-bearer call will always be consecutive (e.g. pairs 0&8 and 1&9), with the second bearer raised when dual-bearer mode is activated being set up on the odd-numbered slot pair. The patterns will always be offset from one another to guarantee a minimum 8MHz spacing between the channels in use, in order to minimise the impact of a static interference source, such as a microwave oven.

When initiating the second bearer set-up, the PP indicates that both bearers are associated with a single connection, and as a result, the voice data will be routed accordingly.

3.11 Scanning for noise

The PP will occasionally use spare TDMA slots to take RSSI measurements on frequency channels. These channels are not associated with a specific transmitter and therefore do not follow a specific hopping sequence.

4 CONFORMANCE TO FCC REQUIREMENTS

The following sections show how the 2G4 system conforms to the appropriate FCC requirements:

4.1 Section 15.247(a)(1)

The hopping channel carrier frequencies are separated by 1024 kHz.

Each bearer is independent and hops at a rate of 100 hops/sec.

The hopping sequence is table generated:

- A table-generated hop sequence is 75 hops long, each channel is used exactly once in the sequence. Therefore, in a 30 second period each frequency channel is used exactly 40 times in that sequence.

The hopping sequence contains 75 logical channels these are mapped-onto 75 physical channels using a mapping table (see section 3.2.3 and Appendix D).

The highest channel occupancy occurs when a FP has 8 active traffic bearers, *i.e.* 16 slots utilised. As shown previously, for a given sequence, in a 30 second period each frequency channel is used exactly 40 times. The active transmission time in a slot is 429.7 μs. Therefore the average time of occupancy on any frequency channel in a 30 second period is:

$$T = 429.7\ \mu s \times 40 \times 16 = 275.008\ ms$$

As a comparison, the lowest channel occupancy occurs when only a single dummy bearer is being transmitted. Because only the A-field is used on a dummy bearer, the transmission is only 109.4 μs long, therefore the average time of occupancy on any frequency channel in a 30 second period is:

$$T = 109.4\ \mu s \times 40 \times 1 = 4.376\ ms$$

The maximum 20 dB bandwidth of the hopping channel is less than TBA kHz.

The 20 dB bandwidth of the receiver input is TBA MHz. (The 3dB bandwidth of the receiver input is TBA kHz).

A packet is sent once *per* frame *per* bearer for the duration of the bearer; packets are not resent.

See section 3.6 for a description of how the receiver gains synchronisation with the transmitter, *i.e.* a dummy bearer.

4.2 Section 15.247(b)(1)

The maximum peak output power of the intentional radiator is TBA W

4.3 Section 15.247(b)(3)

TBA The transmitting antenna does not have a directional gain greater than 6 dBi. TBA

4.4 Section 15.247(g)

In the case of the dummy bearer, which the FP transmits all the time it is powered up and operating, the hopping sequence cycles through the 75 hops in the selected hopping pattern and then repeats.

In the case of a traffic bearer presented with continuous data, which is the normal case --- as this is a voice system, the hopping sequence cycles through 75 hops before repeating.

In the case of a traffic bearer transmitting short bursts, for example, which may happen if a PP has several failed attempts[2] to establish a traffic bearer, then successive traffic bearers will start on different patterns because the PSPN is incremented each frame – see section 3.8.

Note, that this system is a voice system and short burst transmissions are not typical.

4.5 Section 15.247(h)

There is no coordination between transmitters for the purpose of avoiding the simultaneous occupancy of hopping frequencies by transmitters in multiple 2G4 systems.

[2] The protocol actually limits the number of re-tries to 11 before giving up on the connection.

Communication only ever takes place between one FP and a PP, never between two FPs or two PPs. It is actually impossible for a FP to receive a FP packet or a PP to receive a PP packet because their respective ‘sync-fields’ are different.

An FP and a PP that have an active traffic bearer between them share a common hopping sequence and hop sequence adaptation information, *i.e.* swapped channels. However, neither the FP nor the PP transmits this information to a third party, for any purpose whatsoever.

In actual fact, channel collisions between FPs and PPs can and will take place. These may result in reduced voice quality, but this has to be tolerated.

When two transmitters with overlapping radio cells are using the same slot, pattern and phase within the pattern there is sequence collision. The occurrence of multiple, consecutive, corrupted packets is used to identify this. If sequence collision happens on a dummy bearer or a combined dummy/traffic bearer then the FP will randomly select a new pattern. If sequence collision happens on a traffic bearer no action is taken.

REFERENCES

[1] EN 300 175-6 DECT Identities and addressing

[2] TBR 006 DECT General terminal attachment requirements (Annex G)

[3] W11229 Fixed Part Identities for WDCT

APPENDIX A – CHANNEL CENTRE FREQUENCIES

The following table, arranged as a 10 × 8 grid, lists the 79 channel centre frequencies as detailed in section 2.1. The values are in MHz.

	0	1	2	3	4	5	6	7	8	9
0	2401.28000	2402.30400	2403.32800	2404.35200	2405.37600	2406.40000	2407.42400	2408.44800	2409.47200	2410.49600
1	2411.52000	2412.54400	2413.56800	2414.59200	2415.61600	2416.64000	2417.66400	2418.68800	2419.71200	2420.73600
2	2421.76000	2422.78400	2423.80800	2424.83200	2425.85600	2426.88000	2427.90400	2428.92800	2429.95200	2430.97600
3	2432.00000	2433.02400	2434.04800	2435.07200	2436.09600	2437.12000	2438.14400	2439.16800	2440.19200	2441.21600
4	2442.24000	2443.26400	2444.28800	2445.31200	2446.33600	2447.36000	2448.38400	2449.40800	2450.43200	2451.45600
5	2452.48000	2453.50400	2454.52800	2455.55200	2456.57600	2457.60000	2458.62400	2459.64800	2460.67200	2461.69600
6	2462.72000	2463.74400	2464.76800	2465.79200	2466.81600	2467.84000	2468.86400	2469.88800	2470.91200	2471.93600
7	2472.96000	2473.98400	2475.00800	2476.03200	2477.05600	2478.08000	2479.10400	2480.12800	2481.15200	

APPENDIX B – BASE TABLE HOPPING SEQUENCE

The following table, arranged as an 8 × 10 grid, is the base table for the hopping sequence as detailed in section 3.2.1. The sequence is 75 hops long.

	0	1	2	3	4	5	6	7	8	9
0	0	27	38	14	26	49	13	33	73	55
10	16	1	11	54	8	64	2	48	28	61
20	4	40	65	6	23	67	57	42	12	29
30	62	36	47	5	71	43	32	56	21	59
40	39	15	53	18	45	37	74	63	46	3
50	51	31	72	58	9	70	35	69	25	34
60	50	60	68	22	52	24	41	7	17	30
70	19	10	20	66	44					

APPENDIX C – LOGICAL TO PHYSICAL MAPPING TABLE

The following table, arranged as an 8 x 10 grid, is the logical to physical mapping table, as detailed in section 3.2.3.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	0	1	2	3	4	5	6	7	8	9
10	10	11	12	13	14	15	16	17	18	19
20	20	21	22	23	24	25	26	27	28	29
30	30	31	32	33	34	35	36	37	38	39
40	40	41	42	43	44	45	46	47	48	49
50	50	51	52	53	54	59	60	61	62	63
60	64	65	66	67	68	69	70	71	72	73
70	74	75	76	77	78					