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Calculating 802-15-4 Data Rates

Rev. 1.3 — 24 Sept 2019   **Application Note**

Revision history

Rev	Date	Description
1.0	2013	1st release
1.1	Nov 2013	Updated for JN5161/4/8 wireless microcontrollers
1.2	May 2016	Update for JN517x products
1.3	Sept 2019	Update for JN5189

Contact information

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1. Introduction

This Application Note describes how to calculate the effective and actual data rates of an IEEE 802.15.4 wireless network containing nodes that employ the NXP JN51xx wireless microcontrollers (e.g. JN5168, JN5169 and JN5189). The 802.15.4 data frame structure and channel access protocol overhead are described first. Then an example calculation for transferring 1 MB of data is given.

2. Application Overview

The IEEE 802.15.4 standard for Low-Rate Wireless Personal Area Networks (LR-WPANs) supports a maximum over-the-air data rate of 250 kbps for the 2400-MHz band. In practice, the effective data rate is somewhat lower due to the protocol built into the frame structure. Various mechanisms are also employed to ensure robust data transmission. These include channel access algorithms, data verification and frame acknowledgement. The data frame structure and associated protocol overhead are described, and used to determine the maximum data payload and packet transmission time. The channel access and frame acknowledge times are also calculated. An example actual data rate calculation is given for a non-beacon enabled network using unslotted CSMA-CA (with acknowledgements) and a transmission time calculated for 1 MB of data.

> (i) **Note**: The effective handling of the 802.15.4 protocol is critical in order to maintain the maximum data rate of the system. Depending on the system architecture, the processor overhead imposed by the user application can often compromise data rates. The JN51xx devices incorporate a hardware implemented Base Band Controller. This handles the PHY access protocol such as Clear Channel Assessment, auto-acknowledge, packet retries and CRC Checking *without* the need for processor intervention.

3. Channel Access Timing

Non-beacon enabled IEEE 802.15.4 networks use an unslotted CSMA-CA channel access mechanism. This algorithm is shown in the Appendix, Figure 5. Each time a device needs to transmit, it waits for a random number of unit back-off periods in the range {0, $2^{BE} - 1$} before performing the Clear Channel Assessment (CCA).

- If the channel is found to be idle, the device transmits.

- If the channel is found to be busy, the device waits another random period before trying to access the channel again.

Initially, the back-off exponent *BE* is set to *macMinBE*. Using the default value of 3 for *macMinBE* and assuming the channel is found to be free, the worst-case channel access time can be calculated as:

InitialbackoffPeriod + *CCA* = $(2^3 - 1)$ x *aUnitBackoffPeriod* + *CCA*

= 7 x 320 μs + 128 μs

= **2.368 ms**

The CCA detection time is defined as 8 symbol periods.
aUnitBackoffPeriod is defined as 20 symbol periods.
1 symbol period is equal to 16 μs.

> (i) **Note**: If the *macMinBE* value is set to 0, collision avoidance is disabled during the first iteration of the algorithm. In this case, the channel access timing is defined by the minimum Inter-Frame Separation (IFS) constants *aMinSIFSPeriod* and *aMinLIFSPeriod* [1].

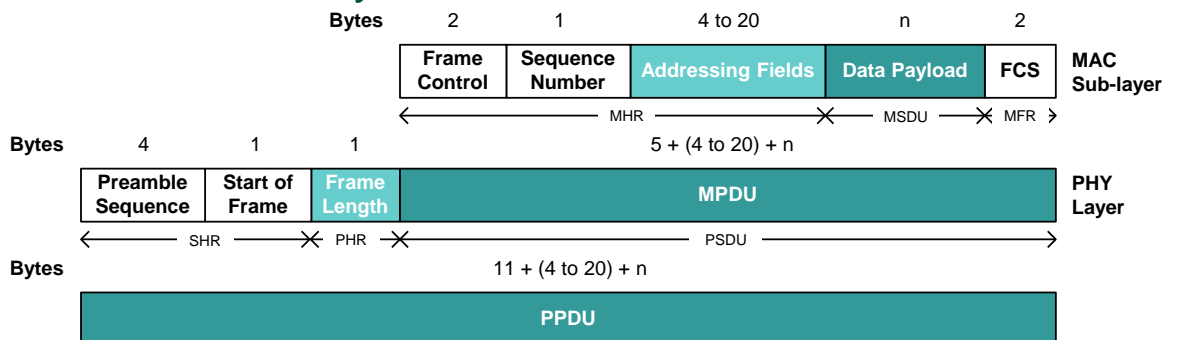## 4. Data Frame transmission

4.1 Maximum Data Payload

Figure 1: Schematic View of Data Frame

The IEEE 802.15.4 standard [1] specifies the maximum number of Bytes that can be transmitted in the MAC data payload as 102 Bytes:

aMaxMACFrameSize (MSDU) = aMaxPHYPacketSize (MPDU) – aMaxFrameOverhead

aMaxFrameOverhead = 25
aMaxPHYPacketSize = 127 (max PSDU size)

The IEEE 802.15.4 standard defines *aMaxMACFrameSize* using the maximum frame overhead regardless of the actual frame overhead size. The IEEE 802.15.4 (2006) standard, supported by the JN51xx devices, allows the maximum data payload to be larger when fewer addressing fields are being used. Using short addressing (16-bit source and destination addresses), the frame overhead is reduced to 13 Bytes, leaving a data payload of **114 Bytes** (see Figure 2).

Bytes: 2	**1**	0/**2**	0/**2**/8	0/**2**	0/**2**/8	variable	**2**
Frame control	Sequence number	Destination PAN ID	Destination address	Source PAN ID	Source address	Frame payload	FCS
		Addressing fields					
MHR						MAC payload	MFR

Figure 2: MAC Protocol Data Unit (MPDU)

*Frame Overhead (Bytes) = Frame ctrl (**2 Bytes**) + SqcNumber (**1 Byte**) + DestPAN ID (**2 Bytes**) + Destination add (**2 Bytes**) + Source PAN ID (**2 Bytes**) + Source add. (**2 Bytes**) + FCS (**2 Bytes**) = 13 Bytes*

> **Note:** For the Star network topology, it is possible to specify only source addressing fields, increasing the maximum data payload to **118 Bytes**. In this situation, the frame is accepted only if the device is a PAN Coordinator and the source PAN identifier matches that of the PAN Coordinator.

4.2 Data Frame Transfer Time

Adding the 6-Byte packet overhead (Preamble and Start of Frame Delimiter [SHR], and Frame Length [PHR]) to the MAC Protocol Data Unit (MPDU), and given a fundamental data rate into the modem of 250 kbps, the frame transfer time is calculated as:

$$\frac{(aMaxPHYPac\,ketSize + SHR + PHR) \times 8}{250 \times 10^3} = \frac{(127 + 5 + 1) \times 8}{250 \times 10^3} = 4.256ms$$

(For a maximum data payload of 114 Bytes with 16-bit source and destination addresses)

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5. Acknowledgement frame Transmission

5.1 Timing

An acknowledgment frame consists of 11 Bytes and is shown in Figure 3. Given a fundamental data rate into the modem of 250 kbps, transmission takes **0.352 ms**. The transmission of an acknowledgement does not use CSMA/CA.
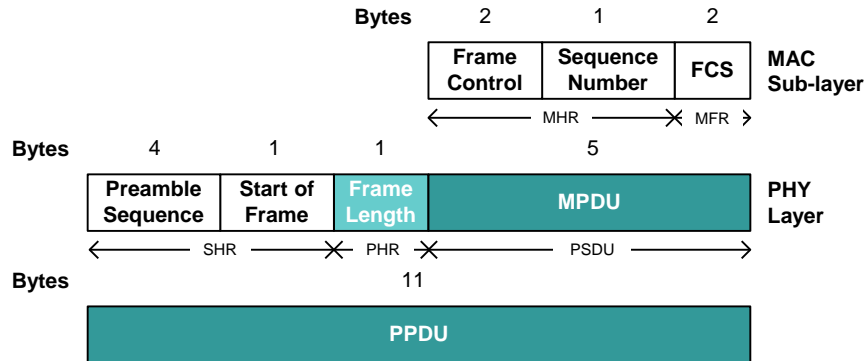

Figure 3: Schematic View of Acknowledgement Frame

The transmission of an acknowledgment frame (in a non-beacon enabled network) commences *aTurnaroundTime* symbols after the reception of the data frame, where *aTurnaroundTime* is equal to **192 µs**. This allows the device enough time to switch between transmit and receive, or vice versa. The timing for an acknowledged transmission is shown in Figure 4 below.
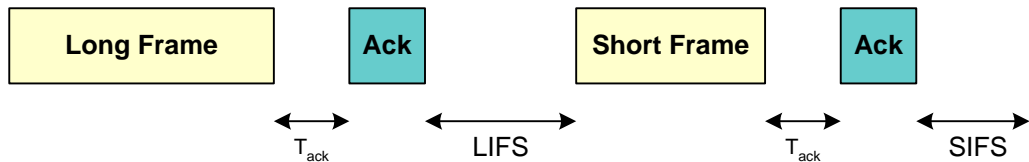

Figure 4: Acknowledged Transmission Timing

1. (LIFS = Long Inter-Frame Spacing, SIFS = Short Inter-Frame Spacing)

To allow the received data to be processed, the acknowledgement frame can be followed by a minimum inter frame separation period (IFS). The length of the IFS period is dependent on the frame size. Frames (MPDUs) of up to 18 Bytes in length must be followed by a SIFS period of at least 12 symbol periods. Frames with lengths greater than 18 Bytes must be followed by a LIFS of at least 40 symbol periods. In real cases, this defined minimum IFS delay is usually absorbed by the CSMA-CA channel access timing. It means for energy saving reason, transmitter IFS is overlapping CSMA-CA and it results in a minimum IFS equals to the back-off time.

5.2 Retry Timing

In practice, it is unlikely that a 0% PER will be achieved. The transmitting node will wait *macAckWaitDuration* symbol periods for an acknowledgment before it attempts a retry, where *macAckWaitDuration* is equal to 54 symbol periods (**0.864 ms**).

6. Effective Data Rate

Here is done the average throughput calculation for a point to point transmission from transmitter perspective. So from the information detailed above, an effective data rate can be calculated based on the following assumptions:

- Non-beacon enabled network

- CSMA/CA algorithm never finds that the channel is busy

- Includes subsequent reception of associated acknowledgment

- No retries are required

- Maximum data payload is 114 Bytes

The calculation is as follows:

CSMA/CA (data frame)	2.368 ms (default random back-off exponent of 3)
Data frame transmission	4.256 ms
Turnaround time (Tx to Ack)	0.192 ms
Acknowledgement transmission	0.352 ms
Total	7.168 ms

Effective data rate = (DataPayloadTime / Total time) x BaudRate

= ((114 x 8)/250)/7.168) x 250

= (114 x 8) / (7.168) = **127 kbps**

7. Actual Data Rate

Here is done the average throughput calculation from transmitter perspective assuming the Receiver is not always available. So an estimate of the actual data rate can be calculated for a non-ideal environment by allowing for retries. Assuming a packet error rate of 25% and all packets that require a retry only require one retry, the total time to transmit a frame with one retry is:

CSMA/CA (data frame)	2.368 ms (default random back-off exponent of 3)
Data frame transmission	4.256 ms
MacAckWaitDuration	0.864 ms
CSMA/CA (data frame)	2.368 ms
Data frame transmission	4.256 ms
Turnaround time	0.192 ms
Acknowledgement transmission	0.352 ms
Total	14.656 ms

The time to transmit a frame with no retries is as calculated for the effective data rate: 7.168 ms.

Therefore, with 75% of data frames taking 7.168 ms and 25% of data frames taking 14.656 ms:

Average data frame transmission time = (7.168 x 0.75) + (14.656 x 0.25) = 9.04 ms

Assuming a 114-Byte payload, the achievable data rate is then given by:

Actual data rate = (114 x 8) / (9.04 x 10^{-3}) = **101 kbps**

So, the transfer time for 1 MB of data will be:

$$\frac{2^{20}}{114} \times 9.04 ms = 1\min 23\sec$$

To improve on this, we could use a random back-off exponent of 1 rather than the default value of 3. In this case, the CSMA/CA channel access time will default to the minimum Long Inter-Frame Spacing (LIFS) of 0.640 ms. This gives an actual data rate of 135 kbps and a transfer time of 1 min 2sec.
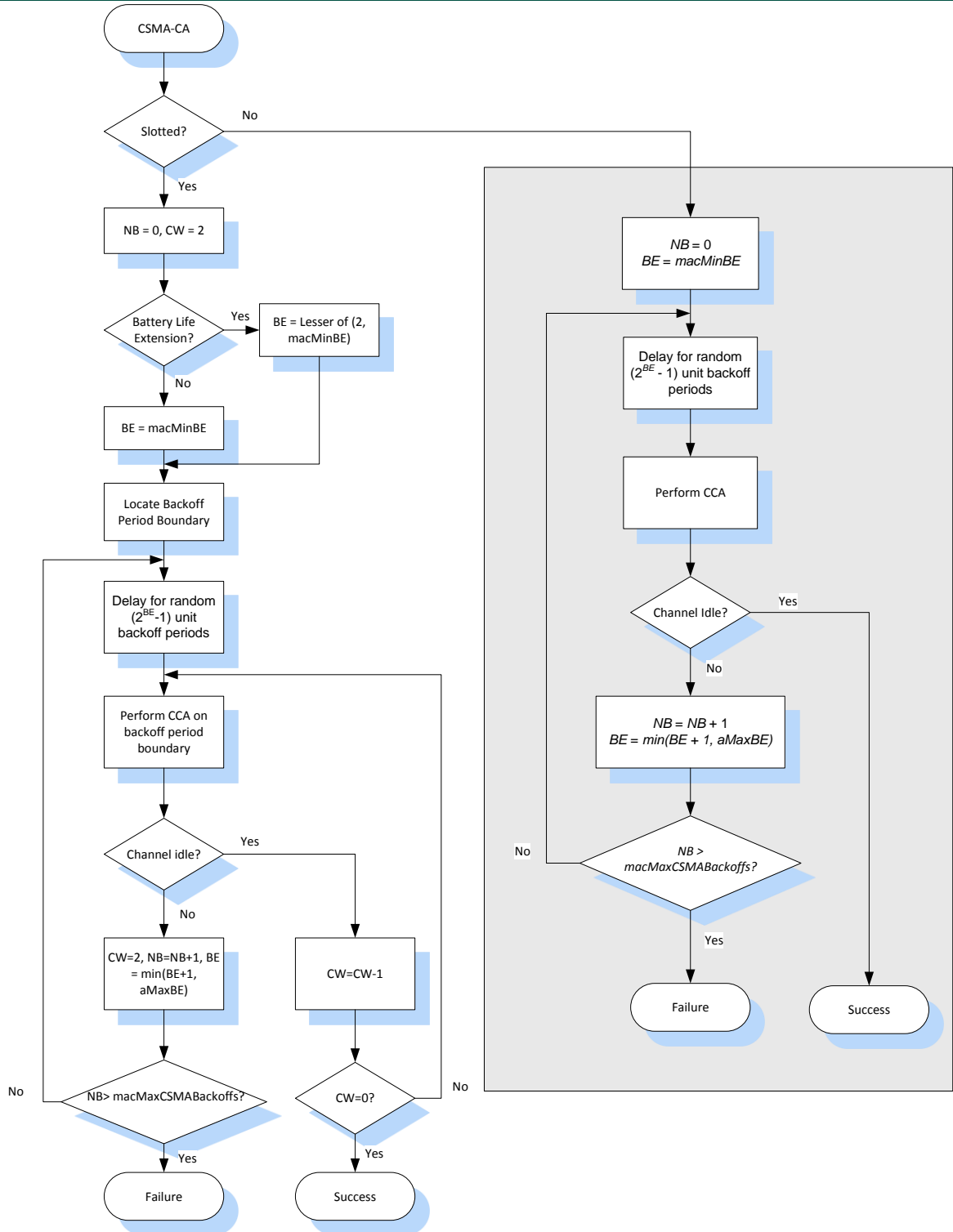
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8. Appendix

Figure 5: The Unslotted CSMA-CA Algorithm

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9. Abbreviations

BE	Back-off Exponent
CAP	Contention Access Period
CCA	Clear Channel Assessment
CFP	Contention-Free Period
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
FCS	Frame Check Sequence
LAN	Local Area Network
LR-WPAN	Low-Rate Wireless Personal Area Network
LIFS	Long Inter-Frame Spacing
MAC	Medium Access Control
MFR	MAC Footer
MHR	MAC Header
MPDU	MAC Protocol Data Unit
MSDU	MAC Service Data Unit
NB	Number of Back-off periods
PAN	Personal Area Network
PDU	Protocol Data Unit
PHR	PHY Header
PHY	Physical layer
PN	Pseudo-random Noise
PPDU	PHY Protocol Data Unit
PSDU	PHY Service Data Unit
SFD	Start-of-Frame Delimiter
SHR	Synchronisation Header
SIFS	Short Inter-Frame Spacing

10. References

[1] IEEE 802.15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs) - https://standards.ieee.org/standard/802_15_4-2006.html

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