

JN-AN-1035

Calculating 802-15-4 Data Rates

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Application Note

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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, JN5174, JN5178 and JN5179). 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.



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. The JN51xx devices also provide a SPI slave (up to 8 Mbps), and also support transfer rates of up to 1 Mbps on the UART.

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:

$$\begin{aligned}InitialbackoffPeriod + CCA &= (2^3 - 1) \times aUnitBackoffPeriod + CCA \\ &= 7 \times 320 \mu\text{s} + 128 \mu\text{s} \\ &= \mathbf{2.368 \text{ ms}}\end{aligned}$$

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 .



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

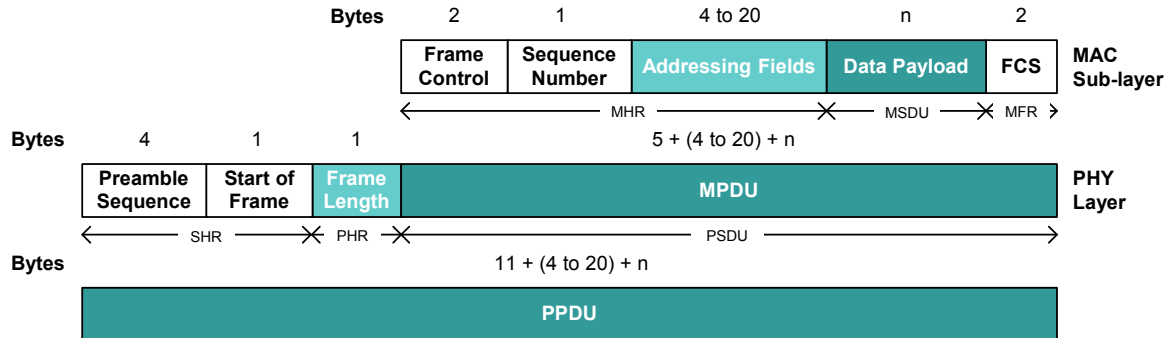


Figure 1: Schematic View of Data Frame

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:

$$aMaxMACFrameSize (MSDU) = aMaxPHYPacketSize (MPDU) - aMaxFrameOverhead$$

$$aMaxFrameOverhead = 25$$

$$aMaxPHYPacketSize = 127 \text{ (max PSDU size)}$$

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)

$$\text{Frame Overhead (Bytes)} = \text{Frame ctrl (2 Bytes)} + \text{SeqNumber (1 Byte)} + \text{DestPAN ID (2 Bytes)} + \text{Destination add (2 Bytes)} + \text{Source PAN ID (2 Bytes)} + \text{Source add. (2 Bytes)} + \text{FCS (2 Bytes)} = 13 \text{ Bytes}$$



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:

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

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

5. Acknowledgement frame Transmission

5.1 Timing

An acknowledgement 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.

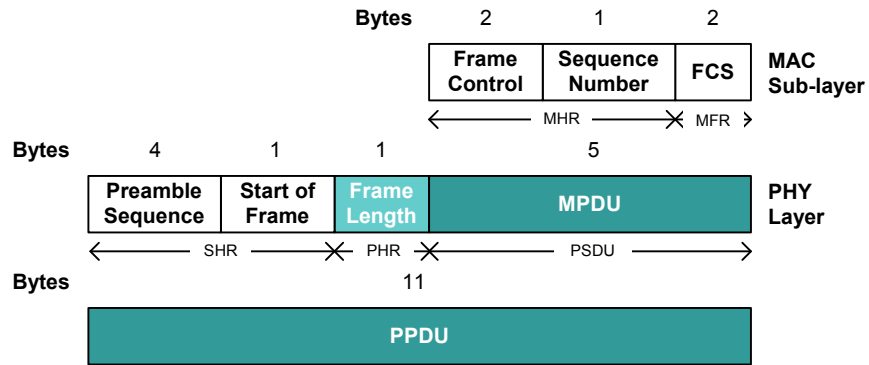


Figure 3: Schematic View of Acknowledgement Frame

The transmission of an acknowledgement 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.

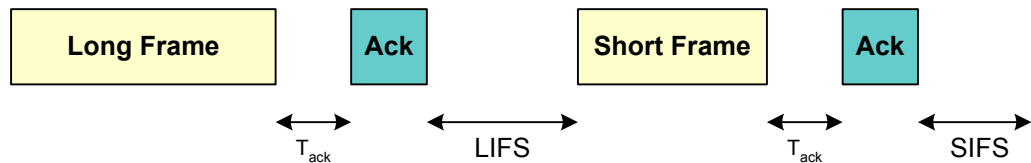


Figure 4: Acknowledged Transmission Timing

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 acknowledgement 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 |
| <i>MacAckWaitDuration</i> | 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:

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

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.

8. Appendix

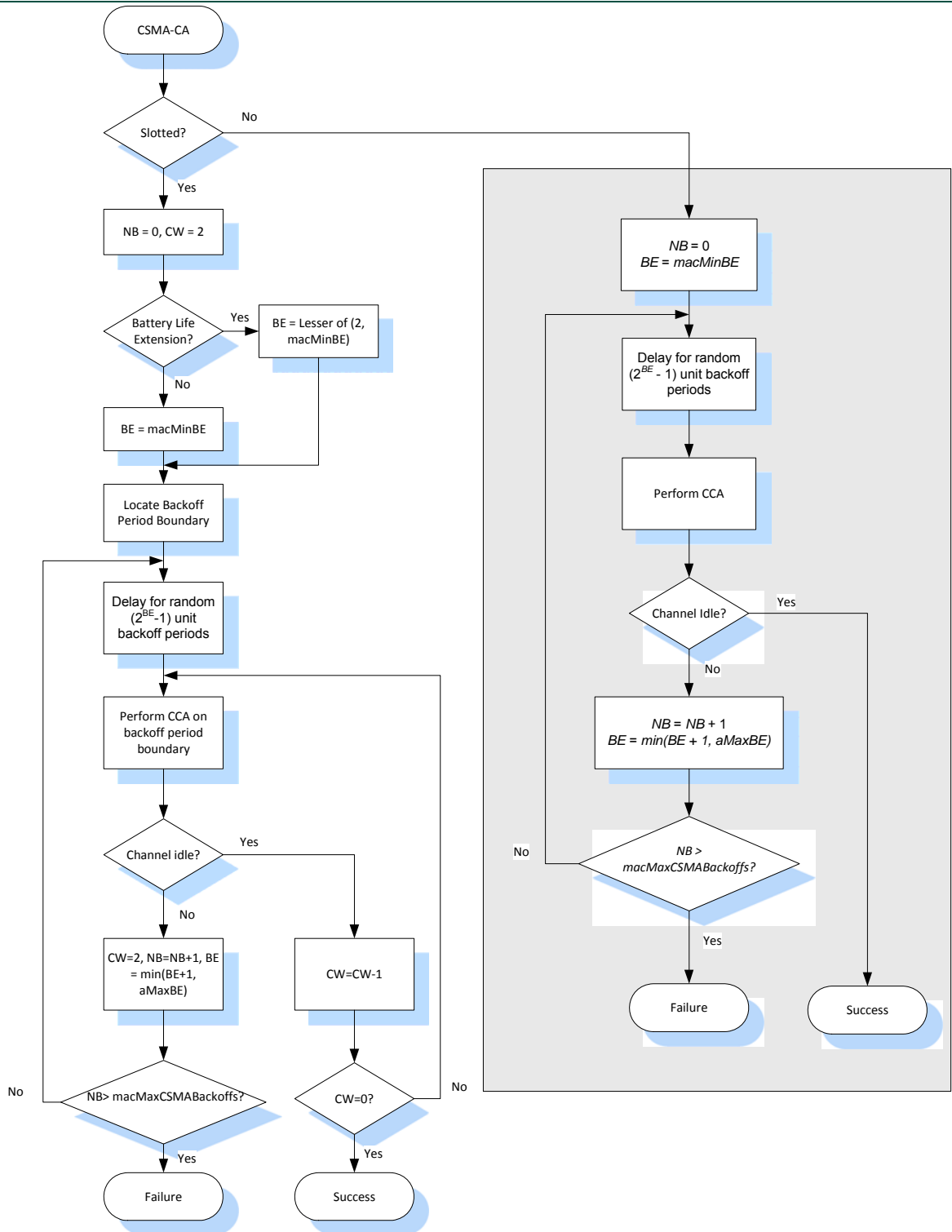


Figure 5: The Unslotted CSMA-CA Algorithm

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) - <http://standards.ieee.org/getieee802/download/802.15.4-2006.pdf>

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