Design and simulations of wireless sensors networks in a long range aircraft

G. Auriol1,2, C. Baron1,2, V. Shukla1,2, J-M. Dilhac1,2, J-Y. Fourniol1,2
1CNRS ; LAAS ; 7 avenue du colonel Roche, F-31077 Toulouse Cedex 4, FRANCE
2Université de Toulouse ; UPS, INSA, INP, ISAE ; UT1, UTM, LAAS
E-mail: {gauriol,cbaron,vshukla,Jean-Marie.Dilhac,fourniol}@laas.fr

Abstract: The work presented in this paper is about the design under specific constraints of a wireless sensors network embedded in a long range aircraft. The paper describes the scientific approach and its results: analysis and selection of a panel of suitable hardware and software technologies, development of adapted solutions, simulations and configuration of these solutions in order to assess various operating strategies of the system. It highlights the several contributions we have at different levels: the definition and implementation of a specific MAC protocol, the elaboration and simulation of adapted data transmission strategies, the comparison of a panel of network topologies, the proposal of a routing protocol and finally the analysis of RF devices.

Keywords: Wireless sensors network, communication and routing protocol, simulations, systems engineering.

1 Introduction

Various points can be tackled during a study on Wireless Sensor Networks (WSN) [1], [2], [3]: electronic design, risk for the human being, management of the energy, telecommunication technologies, signalling and communication protocols, etc. In WSN context, various telecommunication technologies used in Personal Area Network are nowadays potentially answering such points, such as remote monitoring of buildings, care of the elderly, structural health monitoring [4]…

This paper deals with the issues relative to the design of a system based on wireless nodes1, dedicated to the monitoring of temperature variations in strategic places of a long range aircraft. Nodes transmit the measured temperatures and a few others data to a central base station that analyses them. Due to the tricky position of sensors, nodes must be entirely autonomous in energy; thus hardware and software network technologies that will be chosen must use the lowest possible energy.

The section “Technology presentation” highlights the system needs and introduces a selection of suitable technologies. It details various possible technologies at hardware and software levels: several kinds of network topologies, transmission and routing strategies, medium access controls and finally several kinds of hardware devices. The section “Network simulation” presents a homemade simulator using to compare some solutions. The last section concludes and develops some perspectives of this work.

2 Technology presentation

To understand why we selected a panel of technologies to design such a constrained system, let us first describe the expected behaviour of the system. It can be used in either ‘standby’ or ‘activated’ mode. In standby mode, no transmission is allowed: all nodes are in a very low energy consuming state. In activated mode, nodes periodically send data and answer asynchronous base station requests. Every day, each mode will be alternatively used during approximately 12 hours. In standby mode, nodes store around 20 J (or some 2 mA.h at 3.3V). It thus represents a very ambitious challenge to maintain activities in network during the activated mode with so little energy!

Beyond this major constraint on energy consumption, we still have to face the typical issues of wireless networks: the data collisions, the data loses, the range of network, the transmission and signalling mechanisms, and finally the choice of a hardware device able to embed software solutions. When analyzing the use of the aircraft system, two operational modes appear: standby mode and activated mode. In the first one, all wireless nodes are switched to a sleep state and

---

1A node is a device able to perform some processing, gathering sensor information and communicating with other connected nodes in the network.
therefore they cannot transmit. Above is caused by the fact that during the flight there can be no transmission. However, the nodes must be able to be switched to the activated mode in which they can be in sleep state, transmitting state or receiving state, as soon as the user decides it. That brings about a lot of problem new problems concerning waking up the nodes. This section presents several envisaged software and hardware technologies for data transfer adapted to our context. Sub-section “MAC protocols” describes how MAC protocols can avoid collisions when several nodes simultaneously try to transmit data. Sub-section “Data transmission strategies” presents some transmission strategies offering mechanisms to detect and repair losses. Sub-section “Topologies” benchmarks the advantages and drawbacks of single and multi hop networks topologies to deal with the problem of network range. Sub-section “Routing protocols” explains why the application of routing protocols is important and describes some routing protocols improving efficiency of the network. Finally, sub-section “RF devices” presents some available RF devices adapted to the system.

2.1 MAC protocols

Medium Access Control (MAC) is a very important issue in WSN [5], since wireless communication is exposed to many problems, which increase the energy consumption. There are five main situations that increase the energy consumption. As there are several nodes in the network, sometimes it happens that a node receives more than one packet at the same time; these packets are delivered, even when they coincide only partially. All packets that cause the collision have to be discarded and retransmissions of these packets are required, which means supplementary energy consumption. The second reason of energy waste is overhearing, meaning that a node receives packets that are addressed to other nodes. The third one occurs as a result of control-packet overhead. A minimal number of control packets should be used to make a data transmission. Beyond these first three situations where energy is over-consumed, one of the major sources of energy waste is idle listening, that is, listening to an idle channel in order to receive possible traffic. So, to assure very low energy consumption, most of the time nodes are in a sleep state between a reception or transmission state. In sleep state, the required energy is around 1000 less than in case of reception state, even if no node emits data. In standby mode, nodes are in sleep state for long time, while in activated mode nodes have to be periodically awakened to be in reception or in transmission state. However, the use of sleep state increases the risk of data losses. The last reason for energy waste is over-emitting, which is caused by the transmission of a message when the destination node is not ready. Given the above facts, a correctly designed MAC protocol should prevent these energy wastes. Indeed, to deal with these problems, some solutions are available like S-MAC (Sensor MAC protocol) [6], T-MAC (Timeout MAC protocol) [7], WiseMac2 (Wireless sensor MAC, the only CSMA based protocol) [8]. For this project, an ad hoc protocol has been elaborated and applied; it has been called Constant Time Demand (CTD) protocol. CTD is a simple protocol and may be considered as a variation of TDMA protocol but specifically designed for single hop wireless sensor network. It relies either periodic demands sent from base station (or in case of heterogeneous topology, sink) to other nodes, or direct transmission from the nodes to the master in order to send the data. Transmission is efficient due to the synchronization time defined in synchronization phase. It means that each node has its own active period during which it can communicate with the base station. Synchronization avoids the problems of collision, overhearing and, above all, idle listening. It guarantees very low energy consumption, crucial for our network design. However, it should be emphasized that in order to use CTD, the node must be additionally equipped with a Real Time Clock (RTC). However, nowadays, even very cheap and low energy chips have an embedded RTC peripheral.

2.2 Data transmission strategies

In the activated mode, the following data can be sent or received: deactivation, reset, high temperature alert and status check. The status check can be periodic or not, the others necessarily are asynchronous. Let’s note that a periodic status check is the only way to detect an early failure of the node since no data will further be sent by it. On the other hand, a periodic status check considerably increases the risk of collision because of the amount of data on the medium (in case of multi hop topology the amount of data is really considerable). To reduce collision risk perfect synchronization mechanism is needed (by the way of a RTC device for example). To assure the reliability of these data transmission, two strategies could be used: acknowledge based protocol or multiple sending based protocols. A scenario based on no acknowledge protocols provides the lowest power consumption but, to obtain an acceptable reliability, all data must be sent n times (the value of n will be discussed in the conclusion). This scenario is also compatible with nodes equipped with very simple device like RF transmitter. An acknowledge based scenario provides more reliability but is less efficient regarding energy consumption and requires transceiver devices. In the standby mode, activation data should be received by all the nodes which are in a sleep state since a long time. To deal

---

2WiseMAC could also be efficient to manage the transition between standby mode to activated mode because it is based on a longest preamble before sending data.

3If a TDMA based solution is used an additive synchronisation frame is exchange between base station and the nodes.
with this problem, mechanisms like Wake up radio [9] can be used. In addition to the normal RF transceiver, Wake-up radio is based on the use of a secondary ultra-low power radio device in the node. This one runs as here-below described. Initially, all the normal RF transceivers are in sleep mode and only ultra low power radios are in listening mode. The current consumption is there about 500uA. When an event occurs, an ultra low power radio starts the transmission in order to wake up the normal RF transceiver. Then, a proper data is transmitted.

2.3 Topologies

In wireless sensor networks, one usually distinguish two main kinds of network topology, namely the single hop and the multi hop ones. Actually, we developed another approach, called heterogeneous wireless sensor network. Fig. 1 represents the different topologies.

![Image](image1.png)

Fig.1: Single hop, multi hop and heterogeneous topologies

In the single hop topology, the base station is directly connected to each node and therefore can communicate with them directly. There are up to 50 nodes; consequently some of them may speak in the same time. Due to the simplicity of this type of network, a simple synchronization mechanism based on Time Division Multiple Access (TDMA) [10] can eliminate the risk of collision (as only one node can speak at a time), the problem of overhearing (as only one node is listening), as well as the over emitting and idle listening problems (as listening time is set). In sub section “MAC protocols”, we suggested the use of a very simple TDMA protocol named Constant Time Demand protocol. An important feature of single hop networks is that there is no need of routing protocols; it thus decreases the energy consumption. However, a limitation of this solution is that the network range is limited to the node range. Unfortunately, as the distance between the base station and the most distant node is about 70m, it may be difficult to find low power transceiver having sufficient indoor range. One solution could be to increase the range by adding longer antenna; however the length of antenna is limited to 5 cm long. An alternative would be to apply some amplifiers, but this would significantly increase the power consumption.

Thus, a last possible topology to consider is the multi hop wireless sensor network: a message sent from one node has to pass through other nodes before they reach the base station. It practically provides unlimited range, but it results in complexity of MAC protocols and requires routing protocol. Indeed, bad routing solutions can strongly affect efficiency, and consequently leads to higher energy consumption. In “Routing protocols” sub-section, we explain why the application of routing protocols is so important and furthermore describe some routing protocols improving the efficiency of the network.

In the multi hop topology, a message sent by one node has to pass through many other nodes to get to the base station. This gives almost unlimited range; unfortunately the problems presented in single hop network are more difficult to solve. A large number of protocols is available, the most interesting, like S-MAC, T-MAC (based on TDMA protocol) and WiseMac (based on Control Division Multiple Access - CDMA) are briefly presented in the “MAC protocols” sub section. In multi hop topology, problem of routing has also to be faced. Hence all intermediates nodes must be awaken in order to receive and then retransmit the message from other nodes, which obviously increases energy consumption. Some routing protocols minimizing energy are presented in “Routing protocols” sub section. However, neither efficient routing protocols nor MAC protocols can reach the same low level of energy consumption as the one obtained in single hop networks. On the other hand, in multi hop sensor networks, the maximum distance between two neighbouring nodes is shorter, so it is possible to use short range transceiver detail in “RF devices” sub section.

For the project, we developed another approach called heterogeneous wireless sensor network. It consists of two sub-networks: one is a slave network based on very light energy consumption solutions; the other is a master network base in sink device where advanced technology is applied and for which energy consumption is not a problem. Sink is responsible for collecting data from neighbouring node and successively, using master network sends them to the base station.

2.4 Routing protocols

Multi hop wireless sensor networks need some routing protocol [11]. This sub section describes several routing protocols which differ in complexity, efficiency and strategy. Some of them do need a routing table in order to select the best path between a node and the base station, others are based on the broadcast or multicast solutions. Complex and reactive
protocols also are available, like Ad hoc On Demand Distance Vector [12] on ZigBee friendly devices but they need more energy to run. Broadcast protocol based solution is the simplest and the less effective routing protocol. A node, when wants to transmit, sends a broadcast message to all its neighbours. Then, each node repeats this message to others, until the base station receives the message. This solution doesn’t need routing tables. Simple mechanisms can be implemented to avoid too many loops in retransmissions but, due to repetitions of data, this solution is not efficient in term of energy consumption.

Static routing based solution assumes that all nodes know the best path between themselves and the base station. This solution proceeds as follows. First, the base station sends a broadcast message containing a routing table to the sensors. Then sensors use it in order to communicate with a base station. In case of any change in network topology, data in that table is updated and resent by the base station. The problem here is that wireless networks are relatively unreliable and thus, in case of failure of a node, further transmission may be destroyed. To avoid this drawback, more than one path may be included in the routing table. It should be noticed that in case of static routing, the ram memory is essential.

We have designed a specific protocol for the project which does not require routing table. It relies on a local gossip which provides node information about the health status of others nearby nodes. First, each node must find all its neighbours. So, it spreads a broadcast message containing its address and information about its status. When nodes know their neighbours, then each node periodically sends a report message to its neighbourhood. If it receives all responses, no action is performed. However, when one of neighbours is not available to send a response, alert message is broadcasted by all the nodes till it gets to the base station. The same procedure is applied in case of any other high temperature alerts. This solution, comparing to the broadcast routing, guarantees much lower energy consumption and also let us apply status verification, which in case of unreliable environment is essential. The most important feature of this solution is that status verification phase is only performed between neighbouring nodes, thus others nodes are not involved. This considerably improves the efficiency of the network and provides very low energy consumption.

### 2.5 RF devices

In this section we briefly describe radio frequency devices available for nodes which can be used in our system. These devices consist of a microcontroller and a transceiver. Two different groups of nodes, namely low power transceivers/transmitter and long range transceivers are concisely presented below.

Low power transceivers or transmitter are characterized by low current consumption (typically 15-30mA in TX mode at 3.3V) and the maximum range of 40m. Transmitter offers more efficiency in term of sleeping state and generally also in transmission mode but are not compatible with solution based on acknowledges.

Table 1 gives some industrial solutions.

<table>
<thead>
<tr>
<th>Name</th>
<th>$I_{TX}$ [mA]</th>
<th>$I_{RX}$ [mA]</th>
<th>$I_{S}$ [uA]</th>
<th>Data rate [kb/s]</th>
<th>Frequency [Mhz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC1020</td>
<td>23.7</td>
<td>17.3</td>
<td>&lt;1</td>
<td>153.6</td>
<td>402-470</td>
</tr>
<tr>
<td>CC1010</td>
<td>26.6</td>
<td>9.1</td>
<td>&lt;1</td>
<td>76.8</td>
<td>433</td>
</tr>
<tr>
<td>MICAZ</td>
<td>17.0</td>
<td>19.7</td>
<td>&lt;1</td>
<td>250</td>
<td>2400-2483.5</td>
</tr>
<tr>
<td>nRF905</td>
<td>9</td>
<td>12.5</td>
<td>2.5</td>
<td>50</td>
<td>433/868-915</td>
</tr>
<tr>
<td>rPIC12F67</td>
<td>14</td>
<td>N/A</td>
<td>&lt;0.6</td>
<td>40</td>
<td>433</td>
</tr>
<tr>
<td>CC 2550</td>
<td>19</td>
<td>N/A</td>
<td>&lt;1</td>
<td>300</td>
<td>2400-2483.5</td>
</tr>
</tbody>
</table>

Long range transceivers have a large indoor range (up to 100m) but unfortunately consume a quite high energy (about 200mA); however they are compatible with a single hop network topology so they finally can represent an appropriated choice. Table 2 presents some industrial solutions.

<table>
<thead>
<tr>
<th>Name</th>
<th>$I_{TX}$ [mA]</th>
<th>$I_{RX}$ [mA]</th>
<th>$I_{S}$ [uA]</th>
<th>Data rate [kb/s]</th>
<th>Frequency [Mhz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>XBeePRO</td>
<td>270</td>
<td>55</td>
<td>&lt;10</td>
<td>250</td>
<td>2400</td>
</tr>
<tr>
<td>nRF24J40</td>
<td>230</td>
<td>19</td>
<td>&lt;2</td>
<td>250</td>
<td>2400</td>
</tr>
</tbody>
</table>

### 3 Network simulations

Before processing experimental tests on the aircraft, some simulations are necessary to eliminate theoretically potential solutions or to negotiate some customer requirements. Indeed, if the customer wishes, for example, a status checking with a 1 second periodicity, the simulator must be able to show the feasibility of this requirement according to the available energy. A specific simulator has been designed to evaluate the impact of transmission parameters on node autonomy. The main input parameter is the available energy with the assumption that there is no self-discharge in the batteries.

The retained parameters impacting the node autonomy are summarized here:

- Device parameters (TX/RX/sleep current, data TX rate, specific times to switch from state to an-other one...)
- Network parameters (loss parameter, frequency of status check, frequency of estimated alert event...)
- Data size parameters (time format of events, number of planes and nodes, use of CRC...)

\*In a future work, a model of self-discharge will be integrated in the simulator.
Data transmission strategies (with or w/o acknowledges, number of retransmissions...)

Then, the simulator (Fig.2) is able to represent the decrease of available energy according to time; so, we can deduce the autonomy of nodes.

Fig. 2: Snapshot of simulator

The equations used in the simulator are explained for the simple data transmission strategies (see section 2.2 for details of strategies). This strategy doesn’t manage acknowledge neither periodic status check but it is based on systematic retransmission to increase the reliability. First, the time of an event transmission is estimated with the retransmission number $Q$, the frame length $F$, the bit rate $Br$ and specific times of state switching $T_{S-T}$ and $T_{T-S}$:

$$T_{\text{event}} = Q \times \frac{F}{Br} + T_{S-T} + T_{T-S} [s]$$  \hspace{1cm} (1)

The corresponding energy with the energy necessary for data computing $E_{\text{calc}}$ and transmitting power $P_T$ is given by:

$$E_{\text{event}} = T_{\text{event}} \times P_T + E_{\text{calc}} [J]$$  \hspace{1cm} (2)

The total time of node availability depending of the event number $m$ and time spend in sleep mode $T_{\text{sleep}}$ is:

$$T_{\text{total}} = m \times T_{\text{event}} + T_{\text{sleep}} [s]$$  \hspace{1cm} (3)

Corresponding energy:

$$E_{\text{total}} = m \times E_{\text{event}} + E_{\text{sleep}} [J]$$  \hspace{1cm} (4)

Finally, the total working time or node autonomy is:

$$T_{\text{total}} = \frac{E_{\text{total}}}{P_{\text{sleep}} \left( \frac{T_{\text{event}}}{T_{\text{event}} + T_{\text{sleep}}} \right)} [s]$$  \hspace{1cm} (5)

With the same framework, the autonomy of nodes has been calculated for following data transmission strategies:

- No acknowledge, retransmission, periodic status check.
- Acknowledge, periodic status check, fixed frame format (e.g. we can consider that all data have the same length – solution called fixed frame format – or we can implement adaptative mechanisms to optimize frame length – called variable frame format – according to the kind of data: synchronization data, alert event data, check status data, acknowledges...).
- Acknowledge, periodic status check, variable frame format
- Acknowledge, without periodic status check, variable frame format

Appendix A gives details of calculations for each these data transmission strategies.

Some preliminary simulations give interesting result. Fig. 3 shows a comparison between acknowledges and no acknowledges data transmission. These simulations have been done with the same setting of RF device and for a given available energy. To make easier comparison, the abscise axe represents node autonomy. On the left side, the impact of loss rate has been simulated; on the right side the impact of the retransmission numbers has been simulated. Of course, the acknowledge based strategy don’t care about the number of retransmission, while the no acknowledge based strategy is not impacted by the loss rate, except that the number of retransmission has to balance the losses.

Fig. 3: Single hop, multi hop and heterogeneous topologies

With those simulations, we show that:

- a 2-retransmissions without acknowledge strategy:
  - is less efficient than acknowledge based strategy if the loss rate is less than 0.3;
  - is more efficient than acknowledge based strategy if the loss rate is less than 0.5 but more than 0.3.
- a 3-retransmissions without acknowledge strategy:
is less efficient than acknowledge based strategy if the loss rate is less than 0.65;

is more efficient than acknowledge based strategy if the loss rate is less than 0.72 but more than 0.65.

However, to be able to choose an appropriated solution defined by a RF device, a data transmission strategy, a routing protocol and a MAC protocol, the simulations must be completed with experimental tests on an aircraft to have a credible model of loss rate and of device range. Then, more simulations could be done to implement adapted software solutions.

4 Conclusion

The aim of this communication was to describe how we proceeded to design a wireless sensors network dedicated to monitor temperature in an Airbus long range aircraft, and to explain what our results were. We defined the functional behaviour of the system but also determined its components: the communication protocol, the transmission strategy, the network topology, the routing protocol or the RF device. The main constraint on the design was to minimize the energy consumption.

From an exhaustive analysis of current practices, software and hardware components and their performances, we have decided to elaborate a specific MAC protocol, the Constant Time Demand (CTD) protocol, inspired from the TDMA protocol but dedicated to single hop wireless sensor networks. We associated it with an ad-hoc data transmission strategy based on Wake up radio. We also imagined a hybrid network topology: the concept of heterogeneous wireless sensor network, which takes advantages from single hop and multi hop topologies while consuming very little energy. Finally, we designed a specific routing protocol that reveals to be simple and performing considering energy consumption, and also detects node failures.

Simulations campaigns have been processed in order to assess the various operating strategies of the system. They confirmed that the association of technologies and strategies we adopted (CTD transmission protocol, wake up radio strategy, heterogeneous topology, specific routing protocol) provides a solution that meets all specific aircraft manufacturer requirements, improves the network efficiency and uses very little energy.

Next step is to go beyond these simulations and to process real tests on a long range aircraft.

Acknowledgment

The authors wish to acknowledge the French national research agency and 7th Strategic Activity Domain Architecture and Integration of Aerospace valley for their participation in this work which correlates with the project called ATLAS whose purpose is the development of an open source software able to help industrialists to design a product and its associated project simultaneously.

References

Appendix A

Table summarizes the variables used in the simulator to simulate the energy consumption.

Table 1: variables used in the simulator

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{R}/T_{T}/T_{sleep}</td>
<td>Time of receiving/transmitting/sleep mode</td>
</tr>
<tr>
<td>T_{SYNC/END/VER}</td>
<td>Time of synchronization/end/verification phase</td>
</tr>
<tr>
<td>T_{S/R/T}</td>
<td>Time of switch between sleep and receiving/transmitting modes</td>
</tr>
<tr>
<td>T_{R/S/T}</td>
<td>Time of switch between receiving and sleep/transmitting modes</td>
</tr>
<tr>
<td>T_{T/R/S}</td>
<td>Time of switch between transmitting and receiving/sleep modes</td>
</tr>
<tr>
<td>P_{R}/P_{T}/P_{sleep}</td>
<td>Receiving/transmitting/sleep power</td>
</tr>
<tr>
<td>E_{R}/E_{T}/E_{sleep}</td>
<td>Receiving/transmitting/sleep energy</td>
</tr>
<tr>
<td>E_{calc}</td>
<td>Energy needed for uC to perform the calculations</td>
</tr>
<tr>
<td>E_{SYNC/END/VER}</td>
<td>Energy of synchronization/end/verification phase</td>
</tr>
<tr>
<td>n,k,m</td>
<td>Number of verification/synchronization/event</td>
</tr>
<tr>
<td>T_{TOTAL}</td>
<td>Total working time</td>
</tr>
<tr>
<td>F</td>
<td>Length of frame</td>
</tr>
<tr>
<td>F_{syn/data/ack}</td>
<td>Length of synchronization/data/acknowledges frames</td>
</tr>
<tr>
<td>Br</td>
<td>Bit rate</td>
</tr>
<tr>
<td>t_{VER/SYN/EV}</td>
<td>Time between two consecutive demands</td>
</tr>
<tr>
<td>F_{SYN/ACK/DATA}</td>
<td>Synchronization/acknowledge/data frame</td>
</tr>
<tr>
<td>L</td>
<td>Loss rate</td>
</tr>
<tr>
<td>Q</td>
<td>Resent parameter</td>
</tr>
</tbody>
</table>

No acknowledge, with status check

\[
T_{\text{ver}} = Q \cdot \frac{F}{Br} \cdot \frac{1}{1 - L} + T_{S-R} + T_{T-S} [s]
\]

\[
E_{\text{ver}} = T_{\text{ver}} \cdot P_{\text{ver}} + E_{\text{calc}} [J]
\]

\[
T_{\text{total}} = n \cdot T_{\text{ver}} + T_{\text{sleep}} [s]
\]

\[
E_{\text{total}} = m \cdot E_{\text{ver}} + E_{\text{sleep}} [J]
\]

\[
T_{\text{total}} = \frac{P_{\text{sleep}} \cdot (1 - \frac{T_{\text{ver}}}{T_{\text{ver}} + \frac{E_{\text{ver}}}{E_{\text{ver}} + P_{\text{sleep}}}})}{E_{\text{total}}}
\]

Acknowledge, with status check, fixed frame format

\[
T_{\text{syn}} = T_{S-R} + T_{idle} + 3 \cdot \frac{F}{Br} \cdot \frac{1}{1 - L} + T_{R-S} [s]
\]

\[
E_{\text{syn}} = P_{R} \cdot (T_{S-R} + T_{idle} + 2 \cdot \frac{F}{Br} \cdot \frac{1}{1 - L} + T_{R-S}) + P_{T} \cdot \frac{F}{Br} \cdot \frac{1}{1 - L} + E_{\text{calc}} [J]
\]

\[
T_{\text{ver}} = T_{S-T} + 2 \cdot \frac{F}{Br} \cdot \frac{1}{1 - L} + T_{R-S} [s]
\]
\[ E_{\text{ver}} = P_R \times (T_{R-S} + \frac{F}{Br} \times \frac{1}{1-L}) + P_T \times (T_{S-T} + \frac{F}{Br} \times \frac{1}{1-L}) + E_{\text{calc}} \]\[ T_{\text{total}} = n \times T_{\text{ver}} + T_{\text{syn}} + T_{\text{sleep}} [s] \]
\[ E_{\text{total}} = n \times E_{\text{ver}} + E_{\text{syn}} + E_{\text{sleep}} [J] \]
\[ T_{\text{total}} = \frac{1}{P_{\text{sleep}}} \times \left( 1 - \frac{T_{\text{ver}}}{T_{\text{ver}} + \frac{E_{\text{ver}}}{E_{\text{ver}} + P_{\text{sleep}}}} \right) + T_{\text{syn}} \]

**Acknowledgement, without status check, fixed frame format**

\[ T_{\text{event}} = T_{S-T} + 2 \times \frac{F}{Br} \times \frac{1}{1-L} + T_{R-S} [s] \]
\[ E_{\text{event}} = P_R \times (T_{R-S} + \frac{F}{Br} \times \frac{1}{1-L}) + P_T \times (T_{S-T} + \frac{F}{Br} \times \frac{1}{1-L}) + E_{\text{calc}} \]
\[ T_{\text{total}} = m \times T_{\text{ev}} + T_{\text{sleep}} [s] \]
\[ E_{\text{total}} = m \times E_{\text{event}} + E_{\text{sleep}} [J] \]
\[ T_{\text{total}} = \frac{1}{P_{\text{sleep}}} \times \left( 1 - \frac{T_{\text{ev}}}{T_{\text{ev}} + \frac{E_{\text{ev}}}{E_{\text{ev}} + P_{\text{sleep}}}} \right) \]

**Acknowledgement, without status check, variable frame format**

\[ T_{\text{event}} = T_{S-T} + \left( \frac{F_{\text{ack}}}{Br} + \frac{F_{\text{data}}}{Br} \right) \times \frac{1}{1-L} + T_{R-S} [s] \]
\[ E_{\text{event}} = P_R \times (T_{R-S} + \frac{F_{\text{ack}}}{Br} \times \frac{1}{1-L}) + P_T \times (T_{S-T} + \frac{F_{\text{data}}}{Br} \times \frac{1}{1-L}) + E_{\text{calc}} \]
\[ T_{\text{total}} = m \times T_{\text{ev}} + T_{\text{sleep}} [s] \]
\[ E_{\text{total}} = m \times E_{\text{event}} + E_{\text{sleep}} [J] \]
\[ T_{\text{total}} = \frac{1}{P_{\text{sleep}}} \times \left( 1 - \frac{T_{\text{ev}}}{T_{\text{ev}} + \frac{E_{\text{ev}}}{E_{\text{ev}} + P_{\text{sleep}}}} \right) \]

**Acknowledgement, with status check, variable frame format**

\[ T_{\text{syn}} = T_{S-R} + T_{\text{idle}} + \left( \frac{F_{\text{ack}}}{Br} + \frac{F_{\text{syn}}}{Br} + \frac{F_{\text{data}}}{Br} \right) \times \frac{1}{1-L} + T_{R-S} [s] \]
\[ E_{\text{syn}} = P_R \times (T_{S-R} + T_{\text{idle}} + \frac{F_{\text{ack}}}{Br} \times \frac{1}{1-L} + T_{S-T} + P_T \times \frac{F_{\text{data}}}{Br} \times \frac{1}{1-L}) + E_{\text{calc}} \]
\[ T_{\text{ver}} = T_{S-T} + \left( \frac{F_{\text{ack}}}{Br} + \frac{F_{\text{data}}}{Br} \right) \times \frac{1}{1-L} + T_{R-S} [s] \]
\[ E_{\text{ver}} = P_R \times (T_{R-S} + \frac{F_{\text{ack}}}{Br} \times \frac{1}{1-L}) + P_T \times (T_{S-T} + \frac{F_{\text{data}}}{Br} \times \frac{1}{1-L}) + E_{\text{calc}} \]
\[ T_{\text{total}} = n \times T_{\text{ver}} + T_{\text{syn}} + T_{\text{sleep}} [s] \]
\[ E_{\text{total}} = n \times E_{\text{ver}} + E_{\text{syn}} + E_{\text{sleep}} [J] \]
\[ T_{\text{total}} = \frac{1}{P_{\text{sleep}}} \times \left( 1 - \frac{T_{\text{ver}}}{T_{\text{ver}} + \frac{E_{\text{ver}}}{E_{\text{ver}} + P_{\text{sleep}}}} \right) + T_{\text{syn}} \]