ABSTRACT—In this paper the problem of creating a wireless infrastructure to control a vertical transportation system is addressed. The work assumes the use of the standard IEEE 802.15.4 as wireless control field bus. Throughout the paper different network topologies are analyzed together with the network management algorithms. As a result of this analysis the tree topology is selected and experimentally verified as the most suitable for the vertical transportation system.
1. INTRODUCTION

The IEEE 802.15.4 communication standard has opened room for a myriad of possible applications not only in the field of Wireless Sensor Networks [1] but also in fields like active RFID or control of industrial systems [2-5]. In the latter, its use as wireless field bus [6-8] has attracted the attention of the research community due to its suitability for controlling low data rate systems with large number of inputs.

The network topology selection together with the algorithm design for network management are important issues to be taken into account when IEEE 802.15.4 standard is selected as wireless field bus for controlling purposes. In the case of vertical transportation systems control, these are key issues due to the complexity of the communications and the expensive system deployment costs. Communications complexity comes from the diversity in terms of priority, minimum allowed latency and bandwidth. Network management algorithms should be able to deal with low latency, high bandwidth communications that coexist with others featuring large latency and low bandwidth. These algorithms should also be able to minimize power consumption allowing battery operated infrastructure.

In vertical transportation systems the cost associated to the deployment of the control system is mainly due to the installation of wires although other costs as system maintenance cannot be neglected. A wireless control infrastructure able to cope with communication complexity and, at the same time, able to efficiently manage and supervise the network infrastructure is an attractive choice to reduce deployment and maintenance costs.

In this paper the problem of creating a wireless infrastructure to control a vertical transportation system is addressed. The work assumes the use of the standard IEEE 802.15.4 as wireless control field bus. This standard is devoted to the implementation of low data rate, low cost and low power wireless networks (LRWPAN) which fulfils the requirements of a vertical transportation system. The rest of the paper follows with the system architecture that is analyzed in Section 2. Taking into account vertical transportation system requirements, the most suitable network topology will be selected in Section 3. The selected topology is selected to minimize typical problems of RF signal coverage when a moving vehicle acts as an obstacle causing lost nodes or increased power consumption. These problems will be further detected and solved by the network management algorithms devised in Section 4. These algorithms should require low computational resources in order to reduce hardware costs and power consumption of each node of the network. This way system costs are also effectively reduced due to the large number of nodes. Finally experimental results and conclusions are presented in Sections 5 and 6.

2. SYSTEM ARCHITECTURE DESCRIPTION

The traditional scheme of a Vertical Transportation System (VTS) follows the diagram in figure 1(a).

The main parts can be easily identified, like the machine room on the top (1) in charge of controlling the overall VTS. The car is the mobile element of the structure (2) and in every floor; the call buttons can be found (3). Each of these elements will have its counterpart in the wireless implementation of the Vertical Transportation System, shown in figure 1(b). The wireless elements should provide the same performance in terms of system operation while precluding the use of cables to connect them. Looking at figure 1(b) we have three kind of wireless elements: one in the machine room, one in the car and finally, one in each of the floors to perform as call buttons.
The control and information flow in a VTS is typically divided into two subsets with different bandwidth and latency specifications: machine room-car, machine room-floor push buttons. The required bandwidth for the communications machine room-car (BW\textsubscript{MR-C}) is quite superior when compared to the required bandwidth for the communications machine room-floor push buttons (BW\textsubscript{MR-PB}). Moreover, the system must ensure a minimum latency time for the communications between the machine room and the car (LAT\textsubscript{MR-C}), while this requirement is not so stringent for communications between the machine room and each of the push buttons located at each floor of the building (LAT\textsubscript{MR-PB}). In other words: BW\textsubscript{MR-C} >> BW\textsubscript{MR-PB} and LAT\textsubscript{MR-C} << LAT\textsubscript{MR-PB}.

The main reliability problem in a wireless operated system relies on the RF signal coverage, as this signal must be available to each part of the system. Full RF signal coverage is very difficult to achieve in a VTS due to the narrow space available to wave propagation inside the elevator structure. Moreover, the car is a mobile object, typically made of metallic material, which acts as a mobile obstacle for RF signal wave propagation purposes. This obstacle divides the network into two subsets (above and below the car), driving the part below the car to an out of coverage situation if the typical star network topology (point-to-multipoint) is selected. All these issues points out the network topology selection as a crucial task if wireless field bus is selected as control bus for a VTS.

On the other hand, another objective is the reduction of the power consumption of each node inside the wireless control system (P\textsubscript{NODE}) during normal operation, as this will have a direct effect in both the deployment and maintenance costs of the system. Network topology could have a great impact on power consumption as it is well known that long distances RF links consume more power than short distance ones. The power supply source selection task for the call buttons of each floor will be limited by the required power to keep the RF link stable, thus limiting the number of possible low cost solutions.

Finally, the last issue to be taken into account is the CPU processing load for each node of the system as a reduction of the CPU processing load will have a direct impact on the cost of the implemented solution in terms of hardware and power consumption. This is another reason why
the selected network topology together with the algorithm for supervision and control of the network should be as simple as possible and optimized to feature low CPU load.

3. NETWORK TOPOLOGIES FOR A WIRELESS VTS

Several network topologies could be adopted for the wireless control of a VTS. Figure 2 shows the three main options. In the following, we will analyze the main advantages and drawbacks when they are applied to a Vertical Transportation System.

3.1 Star topology

This network topology requires that each node of the network is connected to the main node of the network, the coordinator node (Figure 2a). This is the classical example of a centralized network topology. The main advantage of this network topology is that, in case of a stable RF link, all the messages between each node and the coordinator node, are transmitted directly to the last one, leading to a low network latency. On the other hand, the main drawback is the need for a stable RF link which has a direct impact on both, power consumption and reliability. Achieving a stable RF link is difficult as the car is a metallic mobile obstacle that breaks several RF links when the car is moving through the building floors. This causes increased power consumption, as the transmission power must be raised in order to ensure the RF link quality independent of the car position. This issue is the main reason to discard this topology for the wireless control of a VTS.

3.2 Mesh Topology

This kind of network topology connects each node to all the nodes within its RF coverage (Figure 2b). The latency of this network topology is not as low as in the case of the star topology as a message between the machine room and the call button of the ground floor should pass through several call button nodes located between them. This network topology features reduced power consumption when compared to the star topology as each node is not forced to establish an stable RF link with the coordinator but only within its vicinity. The amount of power reduction will depend on the size of the desired vicinity or, in other words, of the desired latency.

The main drawback of this network topology is related to its management when the car moves through the building. Each time the car moves, some of the nodes lose its RF links with some of the nodes that were within its vicinity, while other nodes increase the nodes within its vicinity. In both cases, the network map should be updated to allow the routing algorithms to optimally route the messages. This increases power consumption as the network map is updated at the cost of RF scanning tasks and, also, routing algorithms increase CPU load.

3.3 Tree topology

Due to the location of the nodes, the most simple implementation of the tree topology for a VTS, is based on the connection of each call button node to the one located in the floor below it (figure 2c). The coordinator node located in the machine room is connected to the call button of the highest floor and also to the car.

The main advantage of this network topology relies on the fact that each node only needs to feature enough RF signal coverage to connect to the nearest one, so that power consumption is drastically reduced. The only RF link that could feature a longer distance (larger power consumption) is the one between the machine room and the car, but in this case, there are no obstacles between these nodes and also, the structure of the building enhances the RF link strength acting as a wave guideline.

The main drawback of this topology is the latency because is not constant and depends on the position of the node within the building infrastructure. The latency time can be very large for the
call buttons located in the lower floors while is minimum for the case of the car and the highest floor of the building. In the case of a message transmitted from call button located at the ground floor to the machine room, this message should pass through all the intermediate call buttons of each floor to reach the machine room. Although for this case the latency is increased by the number of floors, this fact do not compromise the performance of the wireless control system as the required latency and data bandwidth for the communication between call buttons and the machine room is very low when compared to the one required for the communication between the machine room and the car. For the latter, as the tree topology ensures a direct connection between the machine room and the car, minimum latency and maximum bandwidth is achieved. This is the reason why this topology is argued as the optimal achieving low power consumption while ensuring that each connection type features the required bandwidth and latency. Table I summarizes all the features previously described where the Tree network topology can be easily identified as the most suitable to communicate all the nodes within a VTS.

![Figure 2. (a) Star Topology. (b) Mesh Topology (c) Tree Topology.](image)

Table I. Comparison of the three main network topologies for a VTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Star</th>
<th>Tree</th>
<th>Mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BM_{MR-C}$</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>$BW_{MR-PB}$</td>
<td>High</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td>$LAT_{MR-C}$</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>$LAT_{MR-PB}$</td>
<td>Low</td>
<td>Average</td>
<td>Low</td>
</tr>
<tr>
<td>$P_{NODE}$</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>$RF$ Coverage</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Required $RF$ TX Power</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>
4. IMPLEMENTED ALGORITHM FOR THE WIRELESS CONTROL OF A VERTICAL TRANSPORTATION SYSTEM

In order to implement the algorithm for the wireless control of a VTS, we need to perform three basic tasks: network creation, network management and information management and control of the system. In the following these tasks are described for the case of the wireless control of a VTS using the Tree topology.

4.1 Network creation software

This is the piece of software in charge of the network structure. Each node must have an identifier related to its function inside the system. This identifier can be provided in the firmware of the node at the cost of having a different firmware for each node. Another solution consists in providing the identifier to each node at the time of system deployment. Using the latter approach each node can verify its proper operation after deployment and, indirectly, also verify that the network is created correctly using the Tree topology. Once the network infrastructure has been created, it is stored in EEPROM memory to ensure system robustness against power supply failure.

4.2 Information and control management software

The control algorithm in charge of the VTS is divided into two main sections: communications machine room-car and communications machine room-call buttons. The amount of information between the machine room and the car is larger so that the coordinator node of the network, located at the machine room, assigns the highest priority to this communication link. This way this communication link is guaranteed also in case of high traffic between call buttons and the machine room. Moreover, the selected network topology ensures a low latency time for the communication between the machine room and the car as this is a direct RF link. In our case, this will be the latency time specified for the IEEE 802.15.4 standard.

This algorithm manages the network asynchronously using acknowledgment packets between nodes when a message is transmitted. These acknowledge messages are also transmitted asynchronously and are required to solve the problem of identification and retransmission of lost packets.

4.3 Network management software

The network management software is executed in parallel with the control algorithm. It is responsible of the verification of the network structure integrity, not only of possible modifications but also malfunction of any node. It generates a message for the coordinator when it detects any kind of system anomaly and also calls the Network Creation Software to configure the network again taking into account its new structure. In the case of the Tree topology, as each node acts as a repeater for the node located below it, the network management software requires very low CPU load to detect any network malfunction.

5. EXPERIMENTAL RESULTS

System verification has been carried out using OEM boards designed for a VTS. These boards, based on the standard IEEE 802.15.4, use the Freescale MC13213 system on chip solution as both, the CPU processor and the IEEE 802.15.4 Transceiver, and a ceramic PCB antenna to implement the RF TX/RX device in compact form. The software was developed using the IEEE 802.15.4 MAC stack provided by Freescale within the Beestack software. Figure 3 shows the designed boards where it can be noticed that are operated using two standard AA 1.5 V batteries. These boards are also equipped with push buttons in to allow normal operation of the VTS.
In order to validate the suitability of the Tree topology several measurements have been made for a five grounds VTS with the machine room located at the top of the elevator hole. Table II shows the basic comparison for the three topologies. As the optimum is the Tree topology, in the following several measurements are provided. In order to verify the RF coverage, all the nodes have been programmed to use only 1 mW of transmission power (the minimum for Freescale transceivers). The result is that the BER of the system is below 0.1% with the car moving through the VTS. The latency between the Machine Room and the Car has been measured leading always to values below 1.5 ms. Also the latency between the ground floor and the machine room has been measured. More specifically the time between the event when a passenger acts over the ground floor push button and the event when the ground floor push button turns on the led that provides the acknowledgment from the machine room. In all cases this time is below 45 ms which is far below of the typical specification of 500 ms. Figure 4 shows an oscilloscope screenshot of this measurement.

6. CONCLUSIONS

In this paper a new wireless solution suitable of its adoption in a Vertical Transportation System is proposed. It is based on the IEEE 802.15.4 standard and is intended for cost reduction not only of the system deployment but also of the system maintenance. Experimental results show good agreement with the theoretical assumptions as the system feature low-power consumption and low latency for the communications with the highest priority.

REFERENCES

Figure 4. Latency time between the Machine Room and the ground floor Push button

Table II. Comparison of the three main network topologies for a VTS of five floors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Star</th>
<th>Tree</th>
<th>Mesh</th>
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</thead>
<tbody>
<tr>
<td>$BM_{MR-C}$</td>
<td>50 kbps</td>
<td>50 kbps</td>
<td>50 kbps</td>
</tr>
<tr>
<td>$BW_{MR-PB}$</td>
<td>50 kbps</td>
<td>1 kbps</td>
<td>4 kbps</td>
</tr>
<tr>
<td>$LAT_{MR-C}$</td>
<td>2 ms</td>
<td>2 ms</td>
<td>2 ms</td>
</tr>
<tr>
<td>$LAT_{MR-PB}$</td>
<td>2 ms</td>
<td>40 ms</td>
<td>2 ms</td>
</tr>
<tr>
<td>RF Coverage</td>
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<td>&gt; -50dB</td>
<td>Unstable</td>
</tr>
<tr>
<td>Required RF TX Power</td>
<td>100 mW</td>
<td>1 mW</td>
<td>100 mW</td>
</tr>
</tbody>
</table>


12. PCT/US02/27981, Two-Part Wireless Communications System For Elevator Hallway Fixtures.

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