Z-Wave™ as Home Control RF Platform

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ABSTRACT

In recent years wireless home control products like light switches, thermostats, blinds/drapes, appliance controls, energy management and access controls have reached the market. In order to have a true mass-market for home controls, it is important to have a low cost technology, which is easy to install and operate. This requires a lightweight system, which, from the end-user or installer point of view, is easy to install and requires no ongoing network management. The network must be a self-organized mesh network, ensuring error free communication and, in the case of malfunction, using self-healing mechanisms to re-establish a reliable network.

To support a full home control system, the technology must be designed to support horizontal applications, enabling different product types from various vendors to communicate with each other and use each others functionality (for example a movement sensor turns on a light switch).

In order to reach low cost points, the RF platform must be highly integrated, manufactured in low cost processes and the associated software protocol must be very lightweight.

From a product developer's point of view, it is important that the development and manufacturing of products based on the technology is simple. The physical modules must have a small form factor, enabling easy integration into new and existing home control products. Today, home control products are often developed and manufactured in low salary countries to keep the cost to a minimum. It is therefore a significant schedule accelerator to be able to deliver the RF module as a pre-manufactured and pre-tested "component".

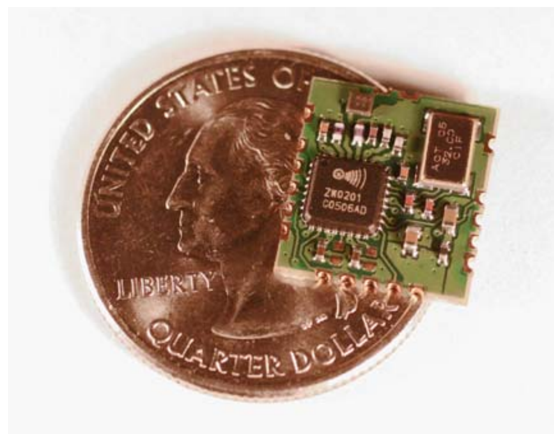

Figure 1 The Z-Wave Module is dedicated for Home Control and contains a complete HW and SW platform including microprocessor, memory, different HW interfaces, crystal, RF circuitry and SW protocol. The Module is 12.5x13.6mm suitable for most applications.

This paper describes how the Z-Wave Technology addresses the needs of the home control network, product development, and manufacturing processes.

Home control applications

The number of interesting home control applications is vast, ranging from simple remote control of light to sophisticated comfort and surveillance systems which use many different resources in the home. The applications can be divided into a number of categories: Comfort Enhancement, Energy Management, Access Control and others.

Comfort Enhancement: A futuristic example would be that, when entering the living room, the drapes go down, the lights dim to a comfortable level, the stereo turns on and your favorite music is played - all initiated by a push on a button or even a sensor detecting your entrance into the room.

Energy management enables you to save money and improve the environment by turning off the light and turning down the heat in rooms which are not occupied, turning off all the lights when the house is empty, switching off the heater/radiator temporarily while the window is open, and so on.

Access control enables you to ensure that all windows/doors are closed and appliances such as irons or coffee makers are switched off before you leave the house. Additionally sensors can detect an intruder entering the home and initiate a series of events such as turning on the light, activating a web cam and sending a message to your mobile phone.

Home control technology considerations

When designing a home control technology three main requirements must be taken into account:

- Ease-of-use
- Reliability
- Low cost

Ease-of-use: When designing a wireless home control technology for the mass-market it is very important to realize that it is the average homeowner or a semi-skilled installer who typically installs the system. The technology must provide simple intuitive installation and require no network management by the user during the lifetime of the installation. Finally the technology must be designed to support horizontal applications, enabling different product types from various vendors to seamless communicate with each other and use each other's features.

Reliability: Robust and reliable RF communication is crucial in order to allow the home control system to handle sensitive operations. For example, if the homeowner instructs the central door locking application to lock and arm the alarm system, he or she must be guaranteed that the instruction is registered and executed.
Furthermore, as RF operates on a shared medium, and RF is sensitive to changes in the environment, protocol algorithms must be applied to make the RF link as reliable as a wired system. The implementation of this robustness includes features such as frame acknowledgment, collision avoidance, random back off algorithms, retransmission, and routing, to achieve reliable links and full home network coverage.

Low Cost: In order to have a true mass-market technology the physical wireless platform must have a very low cost. The right tradeoffs between technology choice and cost must be taken without compromising the reliability of the network.

As many home control products are both developed and manufactured in low salary countries it is important to supply a hardware (HW) and software (SW) platform, which can be integrated without having significant RF and mesh network knowledge. This can be accomplished by supplying a ready-to-use and pre-tested HW module and a well-tested protocol stack, which provides a simple and intuitive interface between the protocol SW and the application SW.

Home control products already exist today, including wireless control and monitoring of lighting, thermostats, movement sensors, air-conditioning, using "ready-to-use" RF platforms containing both hardware and software - see illustration in figure 1.

The RF platform contains microprocessor, memory, RF transceiver, RF front-end and system crystal. The SW protocol assures that the products can communicate with each other in a standardized way.

To meet the complex design requirements of simultaneously achieving low cost, ease-of-use and high reliability the entire wireless platform development process from protocol and module specification to final production must be taken into account.

Home control protocol requirements

The home control protocol needs to address the required network traffic pattern and at the same time support:

- Network flexibility
- Network reliability
- Network ease-of-use

Network traffic pattern

A home control network is characterized by relatively few nodes (20-200) within a 150-600m^2

area in which each node communicates relatively infrequently – every 5-15 minutes. A typical communication consists of 4-6 bytes of payload (i.e. turn on, set dim level, read temperature, read door status etc.). Additionally the majority of home control applications have relaxed latency requirements of 200ms or above. The infrequent traffic, in conjunction with the latency requirements, is served with a network bandwidth of 9.6 kbps.

Network flexibility

A home control network consists typically of a complex mix of AC powered nodes, battery operated nodes, fixed positioned nodes, and moving nodes. All nodes need to communicate with each other seamlessly. The required network behaviour of these node types typically requires too many resources to support them all in one protocol stack. In figure 2 the multiple Z-Wave protocol stack options are shown.

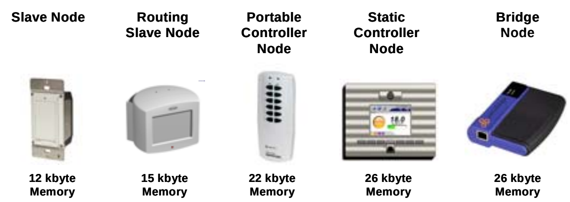

Figure 2 Z-Wave Protocol stacks

The illustration shows how efficiently the protocol stacks can be implemented when performing system partitioning and at the same time maintaining seamless communication between any of the node types. The Z-Wave technology supports the full range of AC-powered, battery-powered, fixed position nodes, moving nodes and, potentially, bridging nodes to other technologies, with a range of Z-Wave protocol stacks.

In the Z-Wave technology, nodes are divided in three fundamental node types (Controllers, Routing Slaves and Slaves), based on their communication behaviour. All node types work seamlessly together and can be mixed in any combination.

- Nodes that need to initiate communication with a large amount of nodes are based on one of the controller protocol stacks.
- Nodes that only need to initiate communication with a well-defined subset of nodes are based on one of the routing slave protocol stacks.
- Nodes that do not need to initiate communication, but only need to react to communications requests from others nodes are based on a slave protocol stack.

Z-Wave supports moving battery powered devices such as handheld remotes and moving sensors within each node type. For controller node types the Portable Controller protocol stack has support for dynamic changes in position. For Routing Slave node types, the Routing Slave protocol stack has support for re-discovery of moving nodes within the overall network topology.

The controller node type contains self-organization management functionalities, which simplify the installation and operation of the network.

For example: when the system enables a controller to become a SUC (Static Update Controller) the changes in network topology are automatically distributed to all relevant nodes in a system by the Static Update Controller (SUC).

The controller node type furthermore contains versatile installation functionalities, enabling different installation strategies ranging from local to central installation.

For example: when the system enables a SUC to become a SIS (SUC Id Server) the installation parameters are distributed to all controllers in the system. If not enabled, only one controller in the system is assigned to install new nodes. The assignment can be transferred from one node to another during the lifetime of the system.

The home control technology needs to handle battery-operated nodes with great power efficiency in order to provide 10 or more years of operation on 2xAAA batteries. It is therefore important that the protocol can provide an efficient wakeup sequence such as powering up based on cyclic wakeup timers, transmitting the frame and returning to sleep mode. Figure 3 shows how Z-Wave enables power efficient operation of a battery-operated thermostat communicating with a temperature control system. The temperature control system is in 'always listening' mode. The thermostat wakes up on a regular basis and reports its temperature, at the same time asking the control system whether any changes in settings are required.

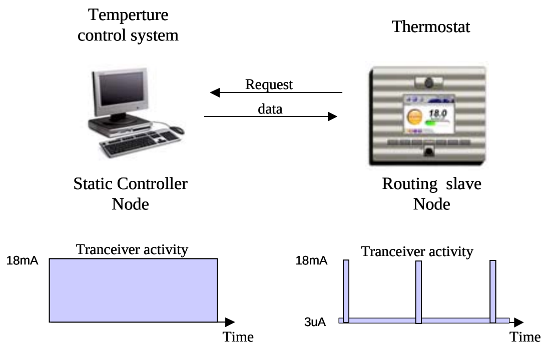

Figure 3 Z-Wave Battery node support

Network reliability

In a medium-sized home two nodes that need to communicate may be beyond direct communication range. The home control system therefore needs to support a mesh network structure enabling the two nodes to use other nodes as routing nodes. Figure 4 shows a typical mesh network with a solid line illustrating the communications path between two nodes, which are beyond direct communication range.

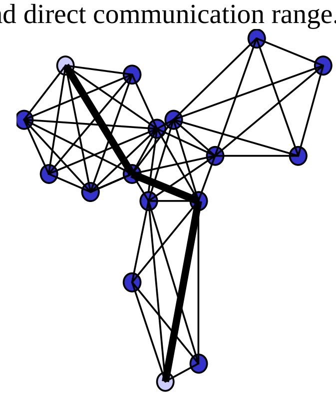

Figure 4 Z-Wave Mesh network

The mesh network also serves as the basis for the self-healing functionalities. RF communications links vary over time due to their strong correlation to the physical environment. For example, when a door open/closes, furniture is are moved, or there are simply many people moving about, RF links may fail because the environment is changing. In these situations the self-healing mechanisms in the technology will automatically reroute the message through other nodes until the message reaches the destination node.

Network Ease-of-use

A typical home control network is installed and managed by the homeowner. This imposes a strong 'ease of use' requirement on the network protocol. Four fundamental elements must be addressed from an 'ease-of-use' viewpoint:

1. Easy network installation
   - Intuitive authentication/identification of nodes
2. Zero management of the mesh network
   - Self organization
   - Robust routing protocol
   - Self-healing
3. Easy association process
   - Self-configuration of the associations between nodes
4. Product interoperability

Easy network installation

The main challenge for easy network installation is to balance the requirements for easy network joining and the requirements for easy identification of the installed devices.

In the literature a number of different network joining philosophies exist, ranging from full 'plug & play' to manual processes with serial number typing. Most of these philosophies have shortcomings in real life due to the very limited user interface on the typical home control product with 1-2 actuators and 1-2 indicators.

The full 'plug & play' installation has severe identification problems in the installation process where many devices are installed at the same time – which light switch is which?

The manual process burdens the user with an input and/or validation process, which is impossible in many simple systems where the user interface is minimal.

One example of a more optimal balance between network join and identification is the Z-Wave installation process shown on figure 5.

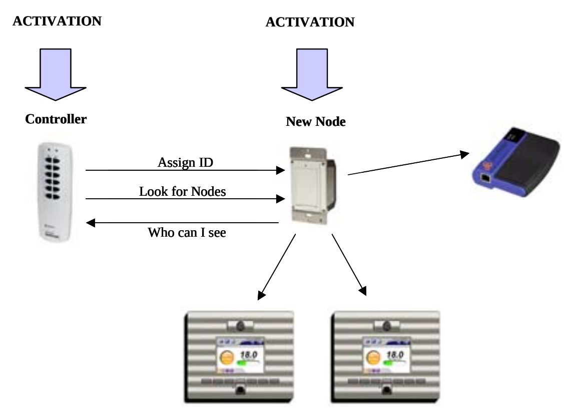

Figure 5 Z-Wave installation

The Z-Wave installation process is very flexible enabling both local and central installation.

The local installation is ideal for small low cost systems (e.g. 5 light remotes + 30 lamp modules), which are installed by the homeowner or an installer. The basic philosophy of the Z-Wave local installation process is that the user activates both the node and the controller in order to install the new product. The activation can be simultaneous or skewed and it can be initiated once or for all new nodes depending on the installation scenario. The new product sends out a request to join the network, which is acknowledged by a controller by assigning an ID to the node. Finally the new node reports back its neighbour list (nodes within direct RF range) to the controller enabling it to have full network topology information.

The central installation is ideal for complex home control Systems with many different products and applications, and which are installed by a professional. The basic philosophy of the Z-Wave Central Installation process is that the Z-Wave technology enables any controller in the system to include new products to the system in coordination with the Z-Wave SIS node. The SIS is typically implemented in a PC or equivalent intelligent device, allowing the installer to have full remote control and monitoring over all steps in the process

<u>Zero management of the mesh network</u>

The central challenge in network management is the fact that the homeowner generally does not fully comprehend that the product he has installed is a part of mesh network. It is therefore important that there is no need for network management in the typical installation. The mesh network must be self-organizing and self-healing.

Self-organizing

In a self-organizing network, nodes are capable of discovering their neighbours and distributing this information to others automatically. In a self-healing network, nodes are capable of redirecting traffic if parts of the mesh are down. One example of a self-organizing network is the Z-Wave network shown on figure 6.

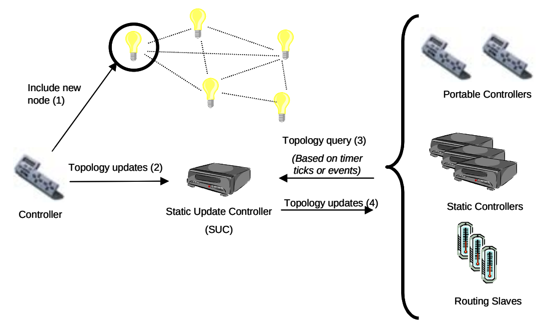

Figure 6 Z-Wave self-organizing network

In Z-Wave every node discovers its neighbours when they are included in the network or upon request. This information is automatically be forwarded to the Static Update Controller (SUC) in the system. The SUC is always 'listening', allowing other nodes to receive/request topology information.

In a self-organizing mesh network the user does not need to consider whether all nodes in the house can communicate directly with each other or whether they need a router along the way. The routing protocol in the mesh ensures that all destination nodes can be reached from any initiator node.

In the literature a wide range of routing protocols are described, each optimised for a given parameter. Some are optimised for handling large networks (distributed algorithms), some for speed and yet others for resource usage.

Given the limited number of nodes in a home control network the Source Routing Algorithm (SRA) is an efficient solution. An SRA provides a good balance between resources needed in the nodes and network size. In an SRA, the initiator generates the entire route through the mesh network to the destination and places this information into the frame header. The route is generated on basis of the topology information provided by the self-organizing functionality. The individual nodes in the route will receive the frame, modify the frame header according to the routing protocol and forward it to the next node in the route. These nodes do not need to store any topology information, which is a significant advantage in a network with scarce resources.

Self-healing

It is important that RF link fluctuations do not generate errors in the home control network – the network must be self-healing.

Figure 7 shows a situation where the communication between garage door and Lamp A fails due to a stainless steel refrigerator door opening (illustrated by the red line) and shows how the technology uses the mesh network to automatically reroute the message using the nodes in the hallway and the foyer to route the frame.

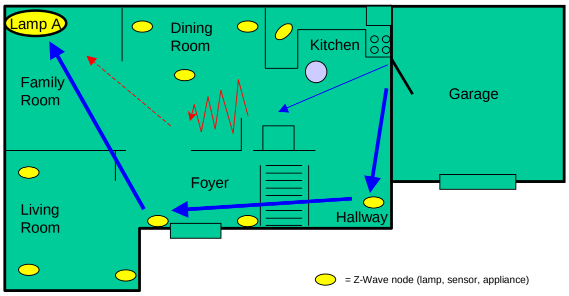

Figure 7 Re-routing through the mesh network

In Z-Wave the self-healing functionality covers two main areas:

- *Fluctuations in the topology* map (e.g. fluctuation of communication links) The routing algorithm receives information from the failing communication and knows which link was defective in the route. This link is temporary removed from the topology and a new route is generated.

- *Changes in the topology* map (e.g. nodes have changed physical position in the network). The Z-Wave orphan algorithm enables a node to request the Z-Wave SUC to initiate a new neighbour search to repair the topology map.

Easy association process

An association between two nodes is a pairing of functionality on one node with functionality on another node (e.g. an activator on a remote controller is paired with the dimming functionality of a particular light dimmer node). The central challenge in an easy association process is to make it as simple as possible for the homeowner or installer. Given the typical home control product, which contains a limited user interface, this requires that the network support self-configuration covering the following elements.

- Provide an Association Wizard, which guides the user through all necessary decisions.
- Sanity check of requested association

In Z-Wave the self-association process builds on the basic Z-Wave 'nodeinfo' frame and standardized command definitions, which enables all nodes to present their supported capabilities in a standardized manner and pair if relevant.

Product interoperability

The central challenge in product interoperability is to balance the full interoperability requirement with the vendor's requirement to be able to differentiate in the market place. Furthermore the interoperability requirement should be reasonably matched to the end user expectation. The average user does not expect that all functionalities are identical in two products – however he or she will expect that all basic functionality is the same or at least behaves logically.

Interoperability is the basis for creating complete home control systems in which different applications from different vendors work together. An example of the total interoperability scope of Z-Wave is shown in figure 8.

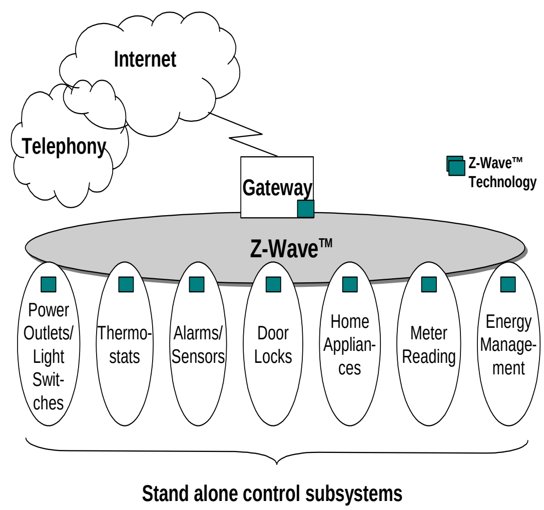

Figure 8 The Z-Wave Protocol enables standardized communication across any product subsystem assuring full coverage.

Product interoperability requires standardization on two levels:

- Command Level: All commands that can be transferred between nodes must be standardized.
- Device Level: All products must be a member of a Device Class that defines which of the commands are mandatory, recommended and optional.

This structure allows products to be interoperable with their basic functionality

In Z-Wave, interoperability is guaranteed by use of the appropriate Device Class Specification and by the Z-Wave Certification Program. The Device Class Specification governs standardization on command and device level for all home control products. The work is carried out in the Z-Wave Alliance ensuring that all relevant market inputs from Z-Wave partners are injected into the Device Classes. The certification program ensures that all products, which carry the Z-Wave logo, have gone through the certification process.

Home control HW requirements

In order to have a home control HW platform, which is highly reliable, the platform must use leading edge technologies throughout, from initial chip design to final product design. This includes wafer technology, layout methodology, assembly methodology, and production test.

A minimal RF platform consists of the following blocks:

- RF transceiver
- RF front-end
- Microprocessor
- Memory
- System crystal

The RF platform is illustrated in figure 9.

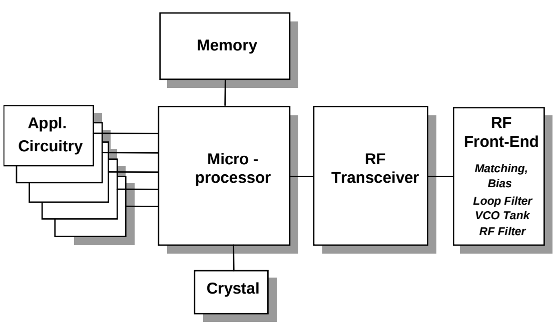

Figure 9 RF HW Platform Block Diagram

In order to provide a mass-market solution the following considerations must be taken into account when designing the RF platform:

- Reliability
- Cost
- Power Consumption
- Size

The overall RF platform must be very low cost because the market for home control products is very cost sensitive. The power consumption must be very low in order to support battery lifetimes of 10 years or more for typical sensors. The RF communication must be reliable, and the size should be small, as modules will be integrated into products with a small physical form factor.

The following section describes the individual RF platform blocks in light of these platform considerations.

Microprocessor platform

The microprocessor platform contains an instruction effective processor (CPU), various HW interfaces, memory and a wake-up timer. An instruction/power effective processor assures fast processing time and low power consumption. To avoid additional chips/circuitry the micro-controller contains as many interfaces (like ADC's etc.) as possible to keep the total system cost down. The memory should be as small as possible and still have room for the protocol and the application SW in order to keep cost and power consumption as low as possible.

In order to have optimum battery lifetime, power management is of high importance and requires careful design of the power circuitry of the entire platform. The power management is an integrated part of the protocol, which means that the microcontroller can ensure that only the circuitry that needs to be powered is on and the remaining circuitry is powered down. A low power timer is needed to have the battery-powered product wake up as required. Using a standard Real-Clock-Timer device usually requires more than 20uA of power. Implementing an on-chip wake-up-timer using only a few microamperes ensures a low power down consumption leading to 10+ years of battery lifetime.

A Frame Handler is implemented to reduce the CPU processing time keeping the power consumption as low as possible. The Frame handler enables the microprocessor to be powered down and only the RF transceiver to be powered up when waiting for frames. Only when the transceiver receives a frame for its specific product is the frame stored, the RF transceiver is powered down, and the microcontroller is powered up to process the received frame.

RF Transceiver

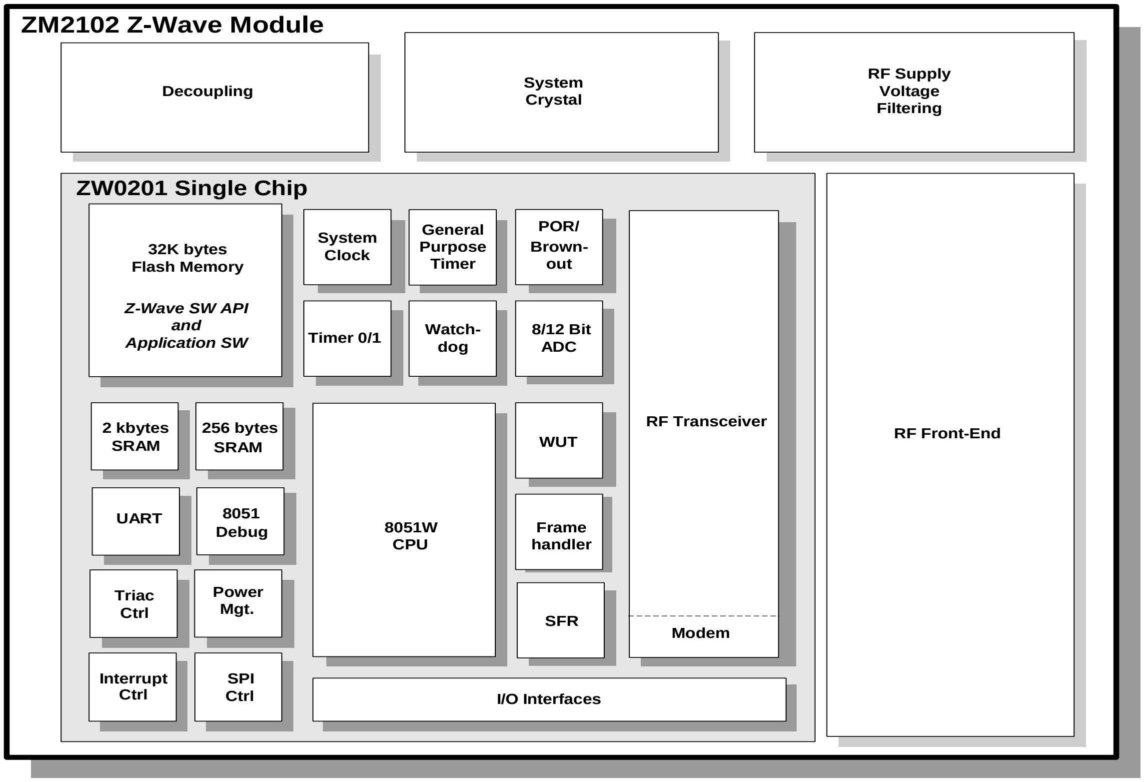

Figure 10 Single Chip solution containing CPU, memory for protocol and application SW, timers, different HW interfaces and RF transceiver. The high integration assures low cost and high reliability.

In recent years, Zensys has integrated the RF circuit VCO tank and loop filter into the single chip, eliminating the need to implement between 10 and 20 passive components. Integrating the passive components on die level does require additional die area, but enables design of high-Q (quality factor) components, reduces interconnection distances, and makes the system more reliable and immune to external noise.
In order to achieve long battery lifetimes the wireless products transmit with as low power as possible. The RF transceiver has a high receiver sensitivity and utilizes a communication frequency which ensures long range. These requirements are met by implementing an effective RF receiver and RF front-end integration chip design in conjunction with an optimal frequency modulation.

The frequency modulation methodology used is also selected with die area usage in mind. As a general rule, the use of high frequencies leads to shorter RF communication range. It is therefore an efficient tradeoff for the RF chips to use sub-Giga hertz license free ISM frequency bands (US: 902MHz-928MHz, EU: 868MHZ – 870MHz) keeping the communication range long, the power consumption low and the die size small.

Microcontroller & RF Transceiver integration level

Integration of microprocessor, memory, various HW interfaces, and the RF transceiver into one single chip not only reduces the overall RF module cost but also reduces the die area and improves the overall RF performance.

Module interconnection

Bringing the overall product cost down also implies the ability to deploy the same RF module in a wide range of products. Using connectors or solder bumps adds to the overall cost. A good alternative is to implement castellation notches, which are plated indentations on the side of the PCB. Castellation notches are suitable for soldering the RF module to the application PCB in a standard reflow soldering process together with the other surface mounted components. The same module can be hand soldered if required.

Production testing

When developing and manufacturing a low cost RF platform, the testing of the individual components and the RF module is of significant importance because testing time comprises a significant amount of RF module cost. Having a single chip reduces the die test (wafer test) to only one die per RF module and the few external digital and RF components can be tested using simple test equipment. The Z-Wave single chip is designed with comprehensive self-test circuitry to ensure minimum wafer test time.

Z-Wave RF module

With the previously mentioned considerations in mind, Zensys has developed a single chip that is supplied on a complete RF Module (ZM2102) for easy implementation into new and existing products. A block diagram of the ZM2102 is shown in figure 10.

The highly integrated single chip contains all circuitry required to control/monitor home control products. Due to the high integration level the ZM2102 only consists of 15 components including decoupling capacitors, crystal, RF filters, enabling a module size of 12.5x13.6mm.

The RF module is optimised for battery applications requiring low power consumption as shown in table 1.

State	**Power consumption**
Power down w. wake up timer running	2,5uA
Transceiver TX @ -5dBm	23 mA
Transceiver RX	21 mA

Table 1 Z-Wave ZW0201 Power Consumption

CONCLUSION

Zensys provides a mass-market home control technology, which is low cost, low power, easy-to-use and reliable. The mesh network Z-Wave system, with its self-organizing and self-healing features, combined with flexible but simple installation procedures, provides an easy-to-use network solution. Z-Wave's versatile and dense protocol stacks and highly integrated single chip furthermore enables the needed low cost points without compromising either network reliability or product versatility. The Z-Wave Device Classes enable product interoperability across applications and between vendors.