# Designing Robust Gateway Nodes for Wireless Sensor Networks

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***Abstract* - Most wireless sensor network applications require some form of gateway node within the network to allow remote access to the information gathered by the network and also to facilitate the control and maintenance of the network. In scenarios where the wireless sensor network operates within a fixed location (eg, within a specific building), the gateway node can be implemented as a wireless network node that is also capable of being connected to a fixed network infrastructure, such as a building's Ethernet network. This provides a very reliable, very high speed connection between the wireless sensor network and any external monitoring and control applications. However, in scenarios where the wireless sensor network is mobile, for example in the case of body-worn or vehicle-mounted sensor networks, or in scenarios where there is no fixed network infrastructure available, a connection of this nature is not possible and other ways must be found to provide a robust and reliable means of connecting to the gateway node from external monitoring and control applications. In this paper we present details of our research into using commercial cellular networks and other wireless systems to provide external links to and from static, nomadic and mobile wireless sensor networks.**

## I. Introduction

In most applications of wireless sensor networks, there is a requirement to be able to extract the information collected within the network for external processing or monitoring and often there is also a requirement to be able to control the operation of the network from an external application for the purposes of configuration and maintenance. In such applications a robust and reliable gateway node, which has the ability to form part of the wireless sensor network and also support a connection to an external network, is an essential component. In applications where the wireless sensor network operates in a fixed location (eg, within a building), the gateway node can be used to provide a bridge between the wireless sensor network and a fixed network (eg, the building's Ethernet network). However, such an approach is not possible in scenarios where the wireless sensor network is mobile, as in the case of body-worn and vehicle-mounted wireless sensor networks, or in situations where a fixed network does not exist. In these scenarios, the external connection to the gateway node must be implemented in the form of a wireless connection. In this paper we examine the design factors that must be taken into account when using a commercial cellular network or other wireless system to provide the external connection to the gateway node. We also present an overview of a test bed that has been assembled to allow these different factors to be investigated in a practical environment.

## II. Considerations When Using Commercial Cellular Networks and Other Wireless Systems

Cellular networks and other wireless access networks rely on a radio link between the network's base stations and the terminals, or mobile stations, to provide access to the network. These links have a significant impact on the quality of the data connection that can be achieved across such networks. In this section we examine each of the key factors associated with data communications across these networks and discuss the impact that they have on the design of the gateway node and the wireless sensor network in general.

### *A. Throughput*

In fixed networks it is possible to transmit data reliably at very high speeds (eg, >1Gb/s). Therefore, when designing a wireless sensor network that incorporates a gateway node connected to such a network, the gateway node can often be assumed to act as a perfect data sink, in that any information sent to the gateway node can be transferred almost instantaneously to devices connected to an external network and information generated externally can be transferred almost instantaneously to the gateway node.

In cellular networks the data throughput that can be achieved is often much lower than that achieved on fixed networks and this is an important consideration when designing the gateway node and the wireless sensor network. One of the most widely deployed cellular technologies is the so-called Second Generation (2G) system known as GSM and this provides packet data connections through the General Packet Radio Service (GPRS). A maximum data rate of around 170kb/s is theoretically achievable on a GPRS network [1], but this relies on many factors being ideal, which is unlikely to happen in a practical situation.

Firstly, the mobile station equipment must be capable of operating on all of the eight timeslots on a GSM radio carrier and the network must be configured to support GPRS transmissions on all timeslots. In many cases, network operators will not be able to dedicate complete GSM radio carriers to GPRS, particularly at busy times, since this will limit the number of channels available to carry voice traffic. Therefore, significantly lower data rates are likely to be available with practical terminal equipment and network configurations.

Secondly, this maximum data rate relies on a perfect, error free, channel existing between the mobile station and the base station, since it does not allow for any forward error correction or the retransmission of packets that are received in error. In cellular networks, near perfect radio channels can exist when the mobile station is not moving and is positioned very close to its serving base station. However, once the mobile station starts to move in relation to the base station and the distance between the mobile station and the base station increases, the decrease in received signal from the serving base station, the increase in interference from surrounding base stations and the rapid fluctuations in the received signal caused by multipath fading can cause a significant degradation in the radio channel quality. Such degradation will cause the GPRS data throughput experienced by a particular user to decrease as the system adapts to provide more forward error correction and packet retransmissions become more common.

Finally, it is important to understand that cellular base stations must share their radio access resources across a wide range of different network users. The maximum theoretical GPRS data rate discussed above assumes that only one mobile station is being served by a particular base station. This may be the case in lightly populated parts of the network or at times of very low network demand, but it is unlikely to be the case in most practical scenarios. Therefore, variations in network loading throughout the day will have a significant impact on the data rates achieved by particular mobile stations.

Some network operators have chosen to upgrade their GPRS networks to support the EDGE technology, which can offer maximum throughputs of close to 500kb/s in ideal conditions [2]. However, all of the practical factors discussed above in relation to GPRS networks also apply to EDGE-enabled networks and the actual throughput achieved in practical scenarios is likely to be only a fraction of this maximum theoretical throughput.

Another widely deployed cellular technology, particularly in Europe, is the so-called Third Generation (3G) UMTS system. This system operates in a higher frequency band compared with the GSM networks and, as a result, UMTS networks do not provide the same levels of coverage as GSM networks and the GSM networks are generally used to provide fallback services in regions where the UMTS network does not provide coverage.

In its basic form, UMTS networks have a theoretical maximum throughput of around 2Mb/s [3], but for the reasons outlined above, significantly lower data rates are achievable in many practical scenarios. Many UMTS network operators have chosen to upgrade their networks to support the High Speed Packet Access (HSPA) technology, which supports maximum theoretical throughputs of around 14Mb/s on the downlink and 6Mb/s on the uplink in ideal conditions [4]. In many practical situations, the throughput achieved on an HSPA-enabled network is likely to be limited to just 1 or 2 Mb/s for the reasons outlined above. The HSPA technology has been further enhanced in the form of HSPA+, which offers maximum theoretical data rates of 28Mb/s on the downlink and 11Mb/s on the uplink [4].

In the near future we are likely to see networks based on a technology known as LTE deployed in many countries around the world and this technology can support data rates in excess of 300Mb/s on the downlink and 80Mb/s on the uplink using an advanced antenna processing technique known as MIMO (multiple-in, multiple-out) [5]. However, systems based on this technology have yet to be deployed extensively and the practical data rate that can be offered over a large proportion of the coverage area is still unclear. Also, it is unlikely that networks based on the LTE technology will offer full national coverage and HSPA and GSM networks will continue to provide fallback coverage in areas where LTE coverage is unavailable.

The gateway node designer also has the option to incorporate other radio interfaces into their design, such as WiFi, which would allow the gateway node to make use of wireless hotspots where they are available. Networks based on the WiMAX technology have also been deployed in some countries and such networks could also be used when the gateway node is situated within their coverage area.

This discussion demonstrates the challenge faced by the wireless sensor network designer when it comes to using a commercial cellular network or other wireless access network to support the gateway link. As an example, the gateway link could provide data rates in excess of 1Mb/s, where the terminal equipment is in the coverage area of a HSPA-equipped 3G network. However, this data rate could fall to just a few kb/s where the terminal equipment is on the fringes of an area that is served only by a GPRS-equipped 2G network.

### *B. Latency*

Another issue that is closely related to data throughput is latency. In a GPRS network, the transmitted data undergo extensive coding and interleaving before they are transmitted across the radio interface and, coupled with the decoding and de-interleaving process, this will introduce a significant transmission delay. Also, as discussed above, the radio resources at the base station will generally be shared amongst a number of different mobile stations and a scheduler within the network will control the access of the individual mobile stations to the shared resource. Therefore, the latency experienced by a particular mobile station can increase significantly, to several seconds, during busy periods as it contends for the base station's resources with other users. 3G networks will offer lower latencies than GSM networks and the HSPA and LTE technologies were specifically designed to offer low latency links.

Again, this demonstrates that the latency experienced on a gateway link supported across a cellular network can vary dramatically depending on the location of the mobile station and the network loading and it is important for this variability to be taken into account when designing the gateway node and the network in general.

### *C. Cost*

In general, it is significantly more costly to access and transfer data across a cellular network than across a fixed network. In the case of cellular networks, each gateway node will require its own SIM card and network subscription, which will generally have an associated monthly or annual cost. This means that it may be attractive from a cost perspective to design a wireless sensor network with fewer gateway nodes when they are connected to a cellular network compared with the case where they are connected to a fixed network. This could have a knock on impact on the routing algorithms used within the wireless sensor network and the scalability of a particular sensing solution.

Also, the lower monthly data caps and the higher charges associated with exceeding these caps tend to make the cost of transmitting data across a cellular network significantly more expensive compared with transferring data across a fixed network. This means that the wireless sensor network designer must pay particular attention to the amount of data that is transmitted across the cellular network and continually examine ways in which this can be decreased with more efficient protocols and data compression techniques.

### *D. Reliability*

As we have already discussed above, the availability and quality of the radio link to a cellular network is dependent on the network coverage within a particular area and the traffic loading on the local base stations. A mobile station can move from areas of good network coverage to poor network coverage in a very short period of time, particularly in urban areas where the radio signal can be easily shadowed by large buildings. The gateway node and the wireless sensor network must be designed such that it can cope with and recover from outages in the gateway link as the network moves between areas of good and poor coverage.

### *E. Network Architecture*

The design of the gateway node and the wireless sensor network must take into account the specific architecture of the cellular network and the effect that this has on the services that can be provided at the gateway node. For example, cellular networks often use local Internet Protocol (IP) addresses and network address translators (NATs) to share public IP addresses between a number of different active users. In this case it is not possible to run servers on the gateway node that will accept incoming data connections and all data connections must be established from the gateway node itself. This raises significant issues when a wireless sensor network needs to be accessed externally for control and maintenance purposes and mechanisms must be found to trigger the gateway node to establish an outgoing connection to an external server.

## III. Gateway Design Techniques

In this section we examine a range of techniques that can be used to address some of the design challenges that were discussed in the previous section.

### *A. Data Categorization and Prioritization*

One technique that can be used to deal with high degrees of variability in the gateway link is data categorization and prioritization. In situations where the gateway link offers a relatively high data rate, these techniques become less important, since it is possible to transmit all of the data that is collected within the network. However, as the data rate of the gateway link decreases, it becomes increasingly important to be more selective about the data that are actually transmitted across this link to ensure that the most important information continues to be conveyed as the data rate falls.

Therefore, the gateway node must be capable of analyzing, categorizing and prioritizing the information that it receives from the sensor nodes. It must also have a mechanism to constantly monitor the actual data rates offered by the gateway link, since this can vary dramatically within a short period of time. Lower priority data could be stored locally within the gateway node and it could be transmitted once the higher priority information has been transmitted or when the gateway link data rate exceeds a certain threshold.

In situations where particular information cannot be transmitted immediately, it is important to understand the value of such information as the delay period increases. For example, some information may have no value if it has to be stored for more than, say, one minute and the information can then be deleted. An example of such information could be the speed of a particular vehicle, which could change significantly during this period and hence be out of date when it is finally transmitted. In some cases the greatest value may be attached to the most recent measurement of a particular parameter, for example a person's heart rate. In these situations, only the most recent measurement is stored for eventual transmission and any earlier measurements are deleted if they have not been sent.

Data categorization and prioritization can also have an important role to play in selecting the protocols that are used to transmit specific information across the gateway link. In some cases it may be necessary to ensure that a piece of information is transmitted across the gateway link and received intact at the other end. An example of information of this type may be a help request generated by a panic button on a body network or an intrusion detection signal generated by an alarm system. In this case, automatic repeat request (ARQ) mechanisms must be used to ensure that any packets that are not successfully received are repeated by the gateway node. In other cases, it may be less critical that a particular piece of information is transmitted intact, especially if it will be superseded by a more up-to-date piece of information within a short space of time. For example, in the case of a body network that is monitoring a person's heart rate, it may not be necessary to ensure that every heart rate measurement is transmitted across the gateway link, provided there are no large gaps in the heart rate information being transmitted. In this case an ARQ mechanism may not be necessary and this will decrease the amount of information transmitted across the gateway link, since retransmissions will not occur.

### *B. Sample Rate Adjustment*

Battery life and power conservation are usually high priorities in the design of wireless sensor networks and it makes little sense to consume energy in collecting a sensor measurement and transmitting this to the gateway node if this measurement is ultimately deleted due to throughput constraints on the gateway link. Therefore, information relating to the data rate currently supported on the gateway link could be made available to the other nodes within the network, perhaps by means of a broadcast message, so that each node can modify its behaviour based on the likely value of the information it is collecting. For example, a node could decrease the rate at which it collects samples as the throughput of the gateway link decreases on the basis that a higher sample rate will result in deleted samples at the gateway node. This could permit the node to consume less power because it can go into a low power sleep mode between taking measurements. In some cases, it may be appropriate for a node to stop collecting and transmitting data completely if the data collected is deemed to be lower priority and is likely to be deleted at the gateway node.

This shows that there could be significant benefits in taking a holistic approach to the design of the wireless sensor network and the gateway node, rather than simply using only the gateway node to manage the gateway link and allowing the wireless sensor network to continue to operate in the same way regardless of the data rate available on the gateway link. However, this requires the development of intelligent control algorithms that allow each node to decide how to react to changes in the data rate available on the gateway link.

### *C. Data Compression*

Given the data rate constraints associated with cellular networks and the data transmission costs, it is important to keep the amount of data transmitted across the radio interface to a minimum. This can be achieved using effective data compression techniques to remove as much redundancy as possible in the transmitted data whilst still conveying the important information. It must also involve designing and selecting efficient transmission protocols that do not add unnecessary data to the transmitted packets. It is important to consider what information can be inferred from the manner in which the information arrives from the cellular network and hence does not need to be transmitted across the cellular network itself. As an example, if connection orientated protocols, such as the Transmission Control Protocol, are used on the gateway link then some information can be associated with the connection itself (eg, the identity of the wireless sensor network) and hence only needs to be transmitted once per connection rather than in every data packet.

Techniques such as these can be used to significantly decrease the amount of raw data that needs to be transmitted across the gateway link, whilst still ensuring that the required information is conveyed.

## IV. CELLULAR GATEWAY TEST BED

In order to investigate and develop techniques and algorithms to cope with the issues outlined above, Multiple Access Communications Limited (MAC Ltd) has developed a test bed based on the architecture shown in Fig. 1. The wireless sensor network consists of a number of MAC Ltd's SensaPak™ wireless nodes, which consist of a low power radio transceiver, a small microprocessor and a number of external interfaces that allow it to be connected to range of different sensors. A photograph of this node is shown in Fig. 2, along with a ruler showing its size in centimetres.

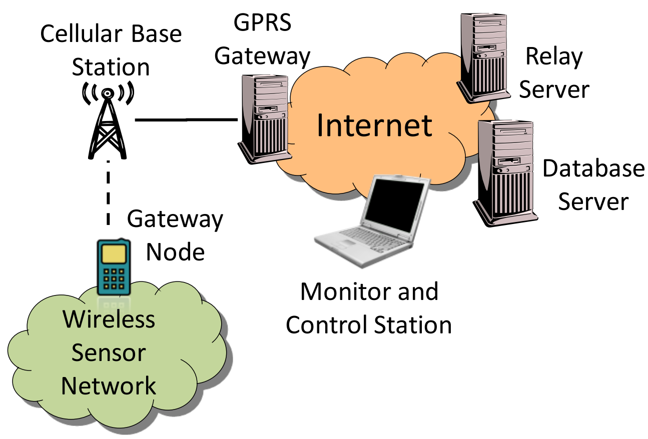


Fig. 1. Test bed architecture.

The gateway node consists of one of the SensaPak™ nodes and an embedded GPRS modem device, which is controlled by the microprocessor on the node. The GPRS modem also incorporates a GPS receiver, which allows the gateway node to determine and report its position. The nodes incorporate adaptive routing algorithms that allow them to discover and join together with other nodes when they are powered on to form dynamic networks without manual intervention.

The test bed also consists of a monitor and control station that is used to collect and display the information from the wireless sensor network, which has been transmitted via the gateway node. The monitor and control station is implemented as an application running on a PC that is connected to the Internet via either a fixed or wireless connection. A screen shot of the PC application is presented in Fig. 3 and this shows the received signal strength, the battery voltage and the temperature of a node being monitored via the gateway node and the gateway link.

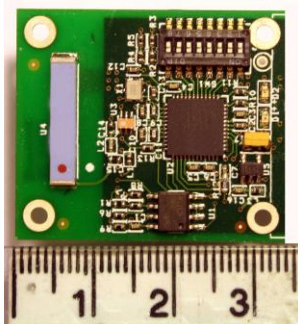

Fig. 2. Wireless nodes used in test bed

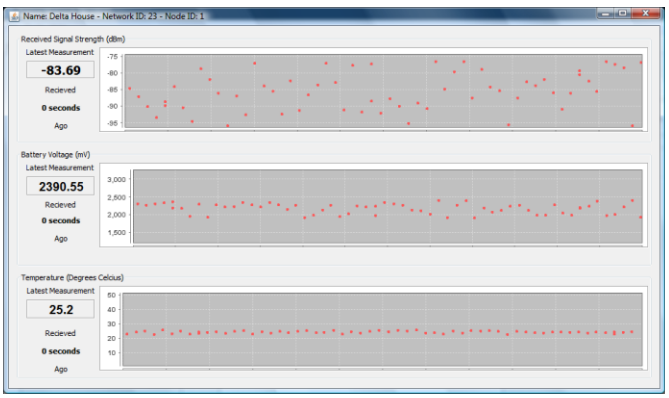


Fig. 3. Screen shot from the monitor and control station PC

The test bed also includes a database server that is used to store information relating to the wireless sensor network and its associated nodes. This allows the investigation and development of techniques to limit the amount of information that is carried across the gateway link by storing important information about the wireless sensor network in the database and accessing this over fixed connections based on a short identity transmitted by the wireless sensor network.

The final component in the test bed is the relay server. This has a public, static IP address and will accept incoming connections from the gateway node and the monitor and control station. This server is used to overcome the problem associated with private IP addresses and network address translation that often occurs within the GPRS network and may also occur within the network to which the monitor and control station is attached.

This test bed is currently being used to investigate and develop algorithms to address each of the practical issues discussed above along with a range of other issues associated with the use of low power wireless networks in sensing applications. Different protocols are being examined for use on the gateway link that are tailored to the various categories of data and the performance of each of these is being characterised from a latency and throughput perspective. Techniques are also being investigated to ensure that the gateway node and the relay server are able to recover from gateway link outages that will occur when the gateway node passes through areas of poor coverage.

Data compression is another key area that is being investigated with the test bed and message formats are being developed to ensure that the amount of data transmitted across the gateway link is kept to a minimum.

In the future, the gateway node will be enhanced to incorporate other wide area and local area wireless technologies such as HSPA, WiFi and Bluetooth.

## V. Conclusions

In this paper we have presented and discussed the key challenges that face a wireless sensor network designer who chooses to use a commercial cellular network or other wireless access network to support a gateway link. We have also examined some potential solutions that can help to overcome these challenges and we have provided details of the work being carried out at MAC Ltd to investigate and further develop these solutions.

## VI. References

[1] E Seurre, P Savelli and P-J Pietri, *GPRS for Mobile Internet*, Artech House, 2003.

[2] E Seurre, P Savelli and P-J Pietri, *EDGE for Mobile Internet*, Artech House, 2003.

[3] H Holma and A Toskala, *WCDMA for UMTS: Radio Access for Third Generation Mobile Communications*, Wiley, 2000.

[4] H Holma and A Toskala, *WCDMA for UMTS: HSPA Evolution and LTE*, Fourth Edition, Wiley 2007.

[5] H Holma and A Toskala, *LTE for UMTS: OFDMA and SC-FDMA Based Radio Access*, Wiley, 2009