# Electronic Shepherd – A Low-Cost, Low-Bandwidth, Wireless Network System

Bjørn Thorstensen
Telenor R&D

Tore Syversen
Telenor R&D

Trond-Are Bjørnvold
Telenor R&D

Tron Walseth
Telenor R&D

## ABSTRACT
This paper reports a new novel low-cost, wireless communication network system, called the "Electronic Shepherd" (ES). The system is innovative in the way that it supports flock behavior, meaning that a flock leader monitors the state of the other elements in the flock using low-cost radio communication equipment. The paper addresses both details of the terminal devices and communication protocols, as well as testing of the system in a real environment. The ES system was originally made to address special needs for sheep and reindeer farmers who were seeking a system to keep track of their animals during the grazing season. The system, including GPS receivers, UHF radio communication transceivers and GPRS modems, contributes a new approach for low-cost networking and service implementation, not only for the purpose of animal tracking, but also for other applications where objects are to be monitored at a low cost.

## Categories and Subject Descriptors
C.3 [**Special-purpose and Application-based Systems**]:– *microprocessor/microcomputer applications, real-time and embedded systems.*

## General Terms
Design, Performance, Experimentation, Verification.

## Keywords
Wireless network, low-power equipment, cost-effective communication, GPS, GPRS, short-range communication, animal tracking, rural computing.

## 1. INTRODUCTION
The ES project started with an inquiry from a local farmer in Lyngen, Norway, who were seeking a system that could be used to keep track of his sheep whilst they were out on grazing land during summertime [1]. Each year, at the end of May, the sheep are left out on their own to graze up in the mountains, and they return at the beginning of September. Unfortunately, some of the sheep never return. Some are caught by predators, some fall off of cliffs in the precipitous terrain, and some remain in the mountains until the snow comes. Keeping track of the sheep is also important to document food safety and food control.

We faced the challenge of making a wireless, mobile communication system that was small enough to be carried by sheep, even newly born lambs, robust enough to survive a summer in harsh weather, and have batteries that last at least one season, that is 3-4 months. The farmer wanted a system that was able to give the position of the sheep at regular intervals and have sensors connected to monitor the "state" of the sheep, for example the temperature or the pulse. He wanted to be able to query a position at any time, and perhaps most important, the system had to be cheap for the farmers to afford investing in it.

Our goal has been to develop a system that uses low-cost terminals with low power consumption at the expense of bandwidth. The present application, as well as many other field applications, does not require a high data rate, as the information transferred between the terminals usually is only a few bytes. Typically, the information can be the output from a sensor, an ID number, a position or a short message. As the application requires that the terminals are left out in the field for a long time, without the possibility to charge or change batteries, a terminal that features very low power consumption is of special concern.

The rest of the paper is organized as follows: Chapter 2 presents a survey of related work, chapter 3 describes the ES system in detail, chapter 4 summarizes the results from the field trials, chapter 5 presents our ideas for future work on the system, chapter 6 describes other possible applications and finally, chapter 7 draws conclusions.

## 2. RELATED WORK
A few projects involving tracking of animals have been reported earlier. Televilt in Sweden has built telemetry systems and mounted them on reindeer, grizzly bears, roe deer and wolf [2]. These are terminals that include GPS and VHF radio communication equipment. Obviously, battery lifetime is of special concern for these devices, as the animals are not easily captured. Also, robustness and weatherproof packaging are important issues. While some of their equipment can be bought ready to use, the terminals built for the purpose of research are very expensive, the cost being much higher than the value of the sheep. The terminals also use VHF radio as an access network, and the range is limited to a few kilometers. However, the main challenges are the same as those in the ES project, namely the need for small, low-power devices able to get their own positions and transfer the data through a wireless communication channel to a central database.


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The SNC project in Luleå, Sweden, reports an application where they want to use mobile communication equipment to provide connectivity to the Saami nomadic community [3]. The project goals are to bring Internet connectivity out to the Saami people by caching web pages and mail. Also, making a telemetry system that can be used to track reindeer is one of the goals. So far, they have not implemented the system, but it seems that what they need is exactly the same as the ES system seeks to be.

The ZebraNet project at Princeton University [4] deals with many of the same problems as the ES project, and is probably the one closest to ours. Indeed, they seek to find low-power, position-aware, wireless communication systems, also including biological sensors, all of which is very relevant to our project. They describe a system for tracking wild animals over a large area, where collars mounted at each animal operate in a peer-to-peer network, and the data from each collar is flooded back to a base station [5]. They plan to test the system at the Mpala Research Centre in central Kenya, which is a very large area that lacks commercially available communication infrastructure. To collect the data from the collars, they have mobile base stations that can be placed in cars, for instance, that drive through the area in order to pick up data from the collars. Due to the peer-to-peer connection, each collar will receive and store data from other collars, and hence the mobile base stations only need to pick up data from a few collars to get data from all of them. Their design goals and trade-offs are very similar to ours. The main difference from the ES project, as will be described in chapter 3, is that we use mobile access points mounted on the animals, and that these terminals automatically send data back to the farmer using available infrastructure. Also, so far we do not use peer-to-peer networking, which perhaps could help solve some of our problems.

From a technical point of view, both Motorola Labs [6] and the ZigBee™ Alliance [7] have reported the use of low-cost, low-bandwidth, wireless network systems. The neuRFon™ network [6] is specifically designed to support wireless sensors that use very low power and low bandwidth. The system only considers fixed network nodes, that is, the mobility and ad hoc aspects are not included. The ZigBee™ Alliance promotes a low-power wireless network targeted at home control, building automation and industrial automation. Both Motorola and ZigBee aim for the new IEEE standard 802.15.4 that is intended for low-power, low-cost, wireless personal area networks [8].

Pakanen *et al.* [9] report a low-cost mobile device, including a microprocessor, which is used for connecting electronic equipment to the Internet. The system can be used for remote control of electronic devices through the Internet; the communication between the intelligent device and the web uses SMS.

Finally, Smart Dust [10] is one of the projects at UC Berkeley involving sensor networks and radio communication nodes. They have also reported a wireless sensor network, where environmental parameters at Great Duck Island have been monitored using Mica sensor nodes based on radio communication [11]. These sensor nodes communicate with a gateway, which again communicates to a fixed access point using WLAN. The access point provides global Internet connectivity. This approach is suitable when the objects to monitor are within a limited area, but will have problems when the objects move far away from the starting point.

# 3. SYSTEM DESCRIPTION

## 3.1 System Overview

To meet the needs of the present sheep-tracking application, the following system specifications were defined:

- The equipment must be small to be mounted on animals.
- The battery must last at least 4 months.
- The equipment must be able to collect GPS position and sensor data several times per day.
- Position and sensor data must be registered at a server at least two times per day.
- The equipment must be able to communicate to the server as long as the sheep are within the designated grazing area.
- Critical sensor data or positions outside a predefined boundary must generate an alarm that is instantly sent to a server.
- The equipment must be properly encapsulated to survive harsh climate and incautious use.
- The system must be cheap to add value for the farmer.

The goal of real-time data query wanted by the farmer had to be dropped, mainly to save power and to keep costs at a minimum. To be able to communicate to a device out in the field, we needed to use a globally available network. There were two choices: the Global System for Mobile communication (GSM), and satellite systems. GSM has coverage throughout most of Europe and the United States, and packet switched data communication can be achieved using the General Packet Radio Services technology, GPRS. Indeed, small terminals based on GPRS modems have gained a lot of focus lately, and are commonly used in what is called M2M communication (Man-to-Machine or Machine-to-Machine). All of the major GSM mobile terminal vendors, like Nokia, Sony-Ericsson and Siemens, promote M2M communication systems [12] [13] [14]. We also considered globally available satellite communication systems, but for the time being, these were found to be too expensive and too power consuming for our purpose. However, we have not abandoned this, as it probably is the only solution in areas where no other communication infrastructure is available.

There are, however, two drawbacks with the currently available GPRS modems; (1) they are too expensive to be mounted on every sheep, and (2) they consume too much power. To overcome this, we designed a system based on the following observations:

**1**. Sheep are flock animals and every flock has one grown up individual that is the flock leader. This implies that the flock leader can act as the flock's gateway to the world and can carry equipment that can be used to communicate with the rest of the flock.

**2**. Flocks will spread in a limited geographical area.

**3**. The amount of data a sheep needs to communicate is small and does not imply the need for high bandwidth communication.

**4**. End-to-end communication to every sheep is not needed all the time. The flock leader can in most cases act on behalf of the flock.

**5**. Global radio networks, (for example GSM or satellite systems) are available almost everywhere in the grazing area.

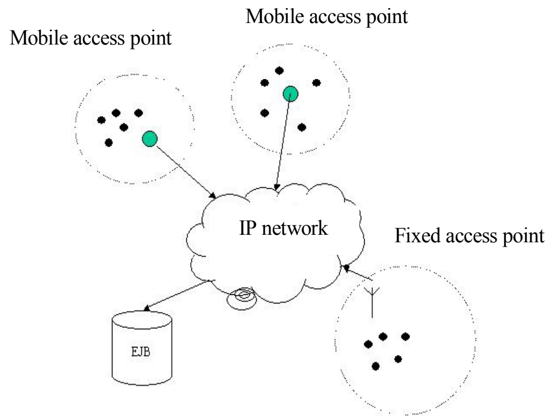


**Figure 1: System overview, showing radio links to the global Internet using GPRS. All data are collected in a database controlled by a middleware server.**

This led to a design based on a communication architecture supporting flock behavior, as shown in Figure 1. Specifically, we designed a central communication unit, called a mobile access point, and a radio tag that can communicate with the mobile access point within a limited range. The mobile access point is a terminal based on a GPRS modem that also includes a GPS module and a low bandwidth, short-range radio unit for communication with the radio tags over the UHF frequency band of 434 MHz. The radio tag is a small, low power tag that has a unique ID number and a means for connecting different kinds of sensors to it. The tag is small enough to be mounted in the ear of a sheep, and because of this, it is also referred to as an ear-tag. This means that we have two different networks, a global access network based on GPRS and a local ad hoc network based on short-range UHF communication. The advantage is obvious; most of the sheep can be equipped with small, low-cost devices, and only the flock leader needs a mobile access point. Hence, the system supports a flock architecture, where the flock leader, in this case the bell sheep, acts as a gateway for the rest of the individuals in the flock. Such a flock structure reflects many groups, and hence there are many applications for such a system, as will be outlined in chapter 6.

We chose the UHF frequency band since it is unlicensed in Europe, it does not require line-of-sight, and there are a lot of integrated circuits available that can be used to develop radio communication devices in this frequency band. Small power consumption for the transmitter is also an advantage. The communication protocol is proprietary, but can be changed to follow the approved 802.15.4 draft standard without major redesign. This solution can be classified as an active RFID tag.

We considered using passive RFID tags, but the limited communication range (up to one meter) and the lack of sensor integration possibilities were disadvantages of this technology. We also considered Bluetooth as a possible technology for radio communication, and we even built a prototype tag using Bluetooth [15], but in the end, size and power consumption issues pointed us toward a communication channel in the UHF band. The unlicensed communication channels in the UHF band are very suitable for applications that require low bandwidth and that transmit data only at a very low fraction of the time. Also, the Internet0 project at the Center for Bits and Atoms at MIT considers using communication channels at even lower frequency bands, bringing embedded IP to small, cheap and low-bandwidth devices [16].

We have also built fixed access points that are mounted at places where the sheep, based on experience, usually are. These access points have both WLAN 802.11 and GPRS as core networks. The 802.11 network stems from the first field trial, when GPRS was not considered. At that time, we had a lot of experience with 802.11 networks and we thought that this technology would be a good choice, but as explained in chapter 4, this was invalidated by the first field trial. It can, however, be used to extend the network into areas that lack GSM coverage.

Since both the access point and the radio tags are mobile, the number of radio tags connected to an access point will vary with time, and the same radio tag can be connected to several access points simultaneously. There is no master/slave relationship between the access point and the radio tag; the access point merely receives and stores information from any radio tag nearby and transmits the information on the GPRS network on request or as scheduled. Figure 2 illustrates a typical scenario, where each access point is associated with a number of radio tags. There are no limits to the number of radio tags connected to each access point, however, they share the same radio channel, and too many radio tags in the vicinity of each other may cause jamming if they try to transmit data simultaneously. The UHF link uses a random access protocol very similar to the well-known Aloha protocol [17].

## 3.2 Mobile Access Point

The mobile access point includes technologies for communication with surrounding radio tags in the UHF band, communication to the rest of the world using a Siemens MC35 GPRS modem, and means for position finding using a µ-Blox TIM GPS module. It also includes a small, Atmega128 microcontroller from Atmel

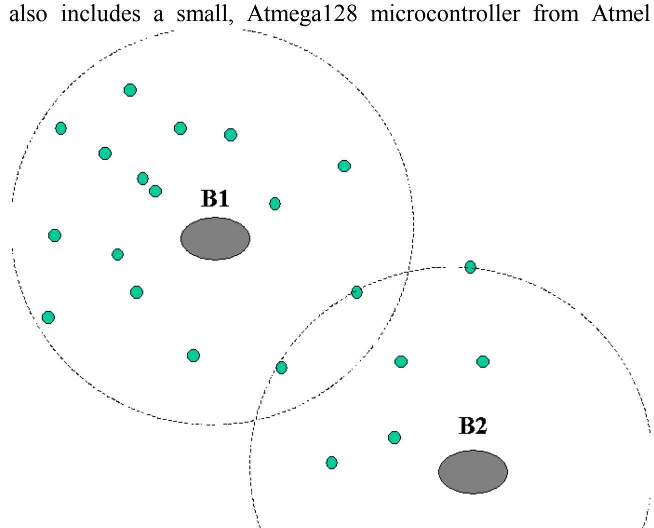


**Figure 2:Mobile access point associations.**

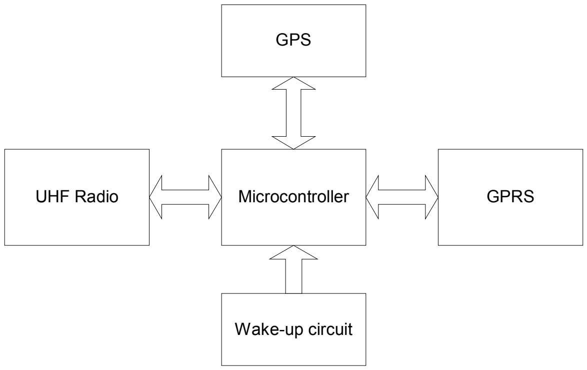


**Figure 3: Mobile access point architecture.**

with non-volatile storage capabilities and software implementing an IP stack. The architecture is shown in Figure 3**.**

To save power, the mobile access point is shut down to sleep mode as much as possible. It has a wakeup circuit that periodically wakes up the microcontroller to check if there are some tasks to perform, and if not, it returns to sleep. The wakeup period can be defined in hardware and ranges from a few milliseconds up to several minutes. In this way, both the microcontroller and the communication equipment can be turned to sleep mode, reducing the current consumption to an extremely low level. A considerable drawback is that we are not able to connect to the mobile access point from the outside when the terminal is using this power-saving mode. However, it is possible to queue messages to the access point that will be sent the next time the access point reports to the server. After sending data, the access point will turn to server mode for a few seconds, allowing anyone to connect to it and send data. To enable a feature that can wake up the access point from outside, the GPRS modem can be turned to a special sleep mode that enables it to wake up on incoming calls or SMS messages. In this state, the current consumption will be about 3 mA; in the complete shutdown mode, the current consumption is about 50 µA. For the sheep-tracking application, the wakeup period is preset to about 1 minute, whereas the on-time is only a few milliseconds, provided the tag has no tasks to perform. Including battery, but excluding packaging, the weight is about 360 grams. Production cost for one access point is about 300 USD.

The terminal is connected to the Internet through GPRS using the PPP protocol. Thus, as long as the connection is established, we can connect to the mobile access point from anywhere in the world. As the GPRS modem gets its IP address on a lease basis, it is likely to change for each connection. To solve this problem, we have implemented a dynamic address lookup service. Any information to be sent to a radio tag can be sent to the mobile access point as an IP packet. The access point will store the data and forward it onto the UHF radio channel when the radio tag makes contact. In this way we are able to communicate with any sheep connected, although the latency can be quite large.

The mobile access point also has a GPS receiver for tracking position. The GPS can be turned off, using only a small amount of current consumption for backup of ephemeral data. As long as the GPS module is turned on at least every two hours, the time to a position fix will be about 8 seconds in average. All surrounding radio tags will be given the same position as the associated access point. The communication range of the UHF radio is about 150-200 meter, and although it would be possible to get a longer communication range, this range was chosen as a trade-off between a long range, enabling communication to as many sheep as possible, and a limited range to get a fairly accurate position of the sheep. There are alternatives to this approach, as discussed in section 5.1.

The ways to configure and use the mobile access point are numerous and will depend upon the application, and in particular, the demands for power handling. Thus, the trade-off between terminal on-time and power consumption is quite clear. For our application, we have chosen the following configuration:

- Wake up the microcontroller at one-minute intervals. If it is time to do something, do it, otherwise go back to sleep.
- Every 3 hours, turn on the UHF radio receiver for 90 seconds to listen for data packets transmitted by nearby sheep. Received data is stored in non-volatile memory.
- Every 3 hours, turn on GPS and get a position fix and time. Data is stored in non-volatile memory.
- Every 12 hours, turn on GPRS modem and transmit the data stored to a remote database.

To keep the terminal from hanging in case it is out of GSM coverage or there are not enough GPS satellites visible, every operation is limited by a timer that, if expired, will automatically shut down the terminal. This configuration results in an average current consumption of 1,4 mA. The battery has a nominal capacity of 3,6 Ah, and if we assume 50% efficiency, the battery will last for about 52 days. For comparison, if the terminal stayed on all the time the battery would last for about 60 hours. Table 1 summarizes the current consumptions for different tasks.

Based on the numbers in Table 1, it is possible to calculate the average current consumption for different configurations. Note

**Table 1: Current consumption for different tasks at the access point.**

| Operation | Current consumption |
|---|---|
| UHF receiver on | 15 mA |
| UHF receiver sleep | 60 µA |
| GPS on | 160 mA |
| GPS off | 10 µA |
| GPRS transmit | 340 mA |
| GPRS idle | 15 mA |
| GPRS off | 0 µA |
| GPRS sleep | 3 mA |
| System processor on | 6 mA |
| System processor sleep | 60 µA |

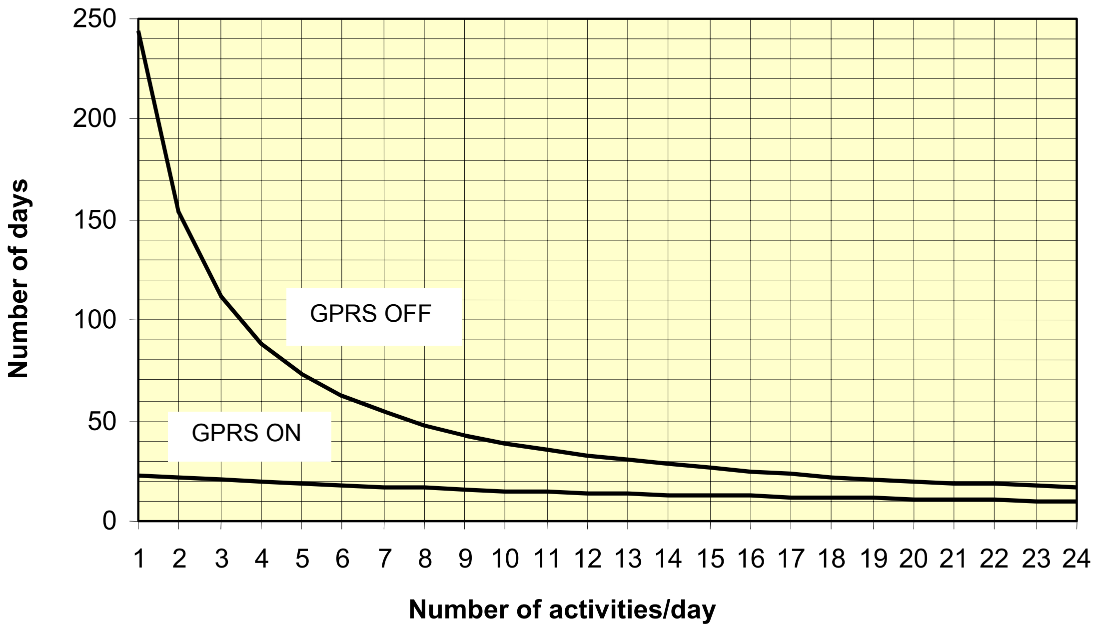


**Figure 4: Battery lifetime versus number of activities per day.**

that the system processor must be on each time either the UHF receiver, GPS or GPRS is on. Also, when the GPRS module is not active, it must be either turned off or in sleep mode. The UHF receiver on-time can be chosen freely, GPS on-time will typically be 50 seconds for the time to fix, and the GPRS on-time, including setup, registration at a network and transmitting of a few bytes of data will typically be 20 seconds. During this time, the transmit state will be approximately 20% of the time, while the modem will be in idle mode the rest of the time.

Figure 4 shows a graph of the battery lifetime as a function of the number of activities per day. An activity is defined as the sequence: Turn on microprocessor, turn on UHF receiver for 90 seconds, get GPS position, turn on GPRS and transmit data to server, go back to sleep. Alternatively, the second graph shows the lifetime if the GPRS modem is left in sleep state, i.e. not turned completely off. In this state, it is possible to connect to the GPRS modem at any time from outside, enabling real-time data capture.

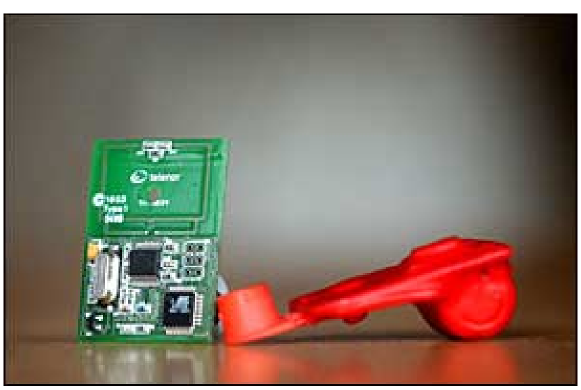

**Figure 5: The radio tag, ordinary version to the left and a packed version to the right, ready to be mounted in the ear of the sheep.**

To keep the data transmission on the GPRS link to a minimum, reducing power consumption, we use UDP over IP. We started out using TCP instead of UDP, but problems related to the memory usage of TCP and TCP windows forced us to implement a simple ACK protocol over UDP. The payload data consists of three bytes of identifier telling what kind of data will follow, for instance radio ID numbers, GPS positions or sensor data, then the data follows immediately. The data is collected in groups having the same timestamp, for instance all radio IDs collected during the 90 seconds the radio receiver is turned on. The receiver will send an ACK to the access point when the data is received, otherwise the access point will try to retransmit the data 4 times. If no ACK is received, the data is stored in the access point and will be transmitted at the next opportunity.

## 3.3 UHF Radio Tag

The second terminal is the radio tag, which is a low-cost, low-power and very small radio transceiver utilizing the UHF frequency band. It consists of two main components, an RF chip that can send and receive signals in the 434 MHz UHF-band, and a microcontroller. The radio tag has functionality that is very similar to the Mica mote [11], but we have chosen to make our own tag, mainly because we needed to adjust the form factor to suit the sheep, but also because this gave us complete control over the communication protocol and the current consumption. A picture of the radio tag is shown in Figure 5, and the architecture is shown in Figure 6.

The radio tag has the same wakeup circuit as the mobile access point, configured to wake up the microcontroller every minute. Under normal use, the radio tag will wake up, transmit an ID number only, listen for a reply and possible commands from the access point, and then go back to sleep. On time is typically below


**Figure 6: Radio tag architecture**

| Packet identifier 1 byte | Tag ID 4 bytes | Payload length 1 byte | Payload | CRC 1 byte |
|---|---|---|---|---|

**Figure 7: Data frame on the UHF communication channel.**

50 ms. The receiver at the access point is on only 90 seconds each hour, so the radio tag will nearly always wastefully transmit its data; only about 2 percent of the transmitted packets will actually be received. This is a consequence of the stringent demands for power saving put on both the access point and the radio tag. Synchronizing the radio tags is not an alternative due to increased power usage, and hence it will be a better alternative to let the radio tags transmit frequently, although the receiver is turned off. The communication range is limited by the maximum allowed power transmitted at the UHF band, which is 10 mW [18], and depends heavily on the transmitter and receiver antenna. The radio tag has a built-in, printed antenna that, due to its small size, limits the communication range between two radio tags to about 150 – 200 meters. Using a receiver with a better antenna can extend the range up to a few kilometers. The tag has a battery with a capacity of 1000 mAh, which under normal use will last for about 2 years. For comparison, if the tag were left on in receive mode transmitting 1% of the time, the battery would last about 60 hours. The weight of the radio tag is only 16 grams, and the size is 32 × 41 mm. For small batches, the production cost is about 20 USD.

Currently, only one sensor has been implemented on the radio tag, namely a small temperature sensor from Dallas using the well-known one-wire transmission protocol [19]. The way it is mounted, it will measure the environmental temperature, not the body temperature of the animal.

Although it would be possible to enable an IP protocol over the UHF link, we have chosen not to do so, mainly to limit power consumption. To keep power consumption at a minimum, a very simple communication protocol with a minimum of overhead is used. When turned on, the radio tag transmits a packet consisting of a one-byte packet identifier, a 4-byte ID, a single byte holding the number of payload bytes, the payload data and a one-byte CRC. The data frame is shown in Figure 7.

The payload will typically be data from sensors. If no data is required, as is the case for most of the packets, the data frame consists of only 7 bytes. The receiver, i.e. the access point, replies immediately with a one-byte ACK to the radio tag. If the tag doesn't receive an ACK, it will try to retransmit the packet two times with about 70 ms intervals. The access point can, when it receives a packet from the radio tag, transmit a command to the tag together with the ACK. Such a command can, for instance, be a request for sensor data from the tag. The data rate used on the UHF link equals a bit length of 128 µs.

Since the radio tags are not synchronized and wake up at different times, there is no way to manage the communication link to avoid data collision. The tags will listen to the link for a short period before transmitting to ensure no one else is transmitting data, but there is no way to avoid collision if two tags decide to transmit at the same time. However, the time used for transmitting data is below 50 ms, and the possibility of data collision is quite low. Hence, this type of Aloha protocol is both simple and efficient for our purpose. To further minimize power consumption, in particular for the UHF receiver in the mobile access point, an Aloha protocol with preamble sampling can be implemented [20].

## 3.4 Fixed Access Point

In addition to the mobile access point, we have implemented fixed access points that can be mounted in the terrain. These access points originate from the early stage of the project when we did not see the possibility of making small access points carried by the sheep. For the first field trial, four access points were mounted on the mountain at places where we knew, based on experience, the sheep would be, at least part of the time.

The fixed access points originally used WLAN 802.11 as a core network. This is a relatively cheap, off-the-shelf technology that can easily be deployed. For areas where the terrain is flat, this is a good choice, but our test site is in no way flat. The line-of-sight issue is a major problem, and we would need a large number of 802.11 links to cover the whole area. In addition, 802.11 radios are quite power consuming, and they provide a bandwidth we really don't need. Using GPRS in areas where there is GSM coverage, and supplying with 802.11 links elsewhere as necessary, seems to be the best approach. Today, we have replaced the 802.11 core network with GPRS, making the access points globally available. The fixed access points consist of several components: a GPRS modem, a PC running a stripped down Linux kernel, a UHF radio receiver, an AD converter and a power regulator. The access points are powered using solar panels and a set of liquid acid batteries. Using solar power, the up time of the access points relies on the weather conditions, but so far this has not been a problem. The architecture of the access point is shown in Figure 8.

## 3.5 Core Network

It is possible to combine the core network elements into different topological configurations.

### *3.5.1 GPRS Core Network*

A GPRS configuration means that the core network is based on GSM/GPRS, and the access points can access the Internet based on a global third party network. This has some advantages. Firstly,

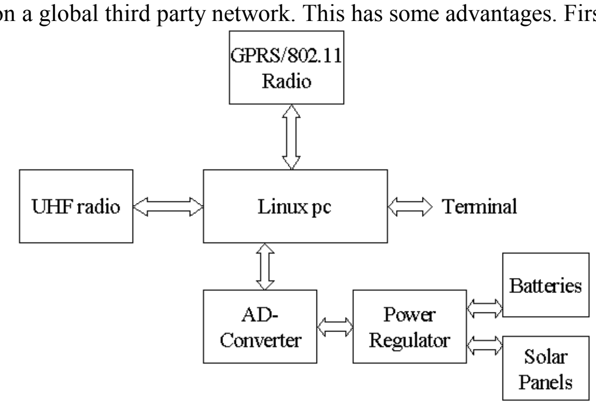


**Figure 8: Fixed access point architecture**

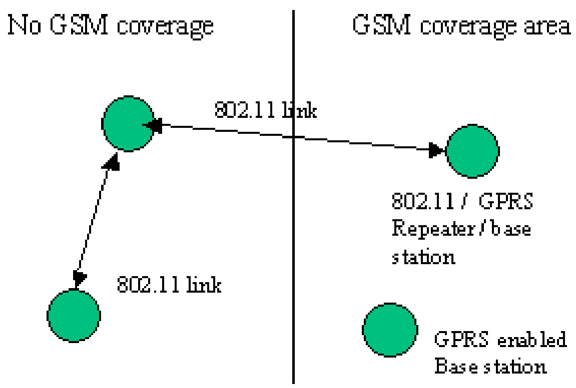


**Figure 9: Mixed network configuration, using 802.11 to deploy network coverage in areas without GSM coverage.**

no maintenance is needed, and secondly, modems are quite cheap and easy to install and use. For areas with good GSM/GPRS network coverage, GPRS configuration is the best choice. In Norway, this will apply for most of the lowlands and some of the mountain areas that have a lot of tourists.

### *3.5.2 802.11 Core Network*

An 802.11 network configuration was our initial approach. This means that the core network is 802.11 only, and implies the need for installation of fixed network nodes in the terrain. These are fairly expensive installations that need maintenance from time to time. If the GSM network is not available, this is one possible solution, but for hilly areas where line-of-sight is a problem, this is not a good approach. In this case we would need a lot of installations in the terrain to obtain good coverage. In flat areas, only a few installations are needed to cover a large area.

### *3.5.3 Mixed GPRS/802.11 Core Network*

An interesting approach is the mixed GPRS/802.11 configuration. At our test site the GSM coverage varies, and in some areas it is absent. The most viable approach uses GSM wherever it is available and extends the coverage using 802.11 in areas where GSM is absent. This means that we need to deploy multi-interface access points in border areas. Figure 9 illustrates this.

As for the GPRS network, the network nodes are interconnected using an IP network. The GPRS network nodes are assigned global IP addresses from the network. As we don't have access to the same address space for the 802.11 networks, we use a private address space for these links. A NAT located in the 802.11 repeater translates packets between the global and private address space.

## 3.6 Persistent Storage and Logic Model

All data generated by the access points and radio tags needs to be collected, processed and presented to the end-users. End-users in this context will be farmers, government authorities, veterinary inspectors, retailers and consumers. Government authorities can use the data, for example as a basis when they calculate compensation to the farmer for animals that have been caught by predators; veterinary inspectors can check that the animals are healthy before they are slaughtered; retailers and consumers can check the history of a product – i.e., the documentation of the animal's life. The interesting data to be stored and accessed is dependent on the type of end-users, and this must be kept in mind when designing the data storage system. Also, the data presentation is likely to be different, depending on the end-user groups.

### *3.6.1 Middleware Server*

An Enterprise Java Beans (EJB) [21] middleware application server implements the ES logic model, provides a set of interfaces to end-user applications and provides persistent storage. All services provided by the network are presented as EJB remote interfaces. In addition, all services provided to the network nodes (i.e., access points and radio tags) are also presented as EJB interfaces. A MySQL database implements the EJB entity bean model and the data storage. At the upper layer is an Apache Tomcat web-server that serves JSP based end-user applications.

One of the reasons that we chose the EJB approach was that we needed open interfaces with a common well-known protocol. By utilizing protocols like RMI and SOAP [22], most applications will be able to access the server. However, the elements in the infrastructure pose complications when using this model. Access points and radio tags that want to talk to the server cannot speak any of the above protocols, although SOAP might be possible as it's basically XML tags. Only sockets are currently available. In addition, there will be a problem if many radio tags or access points try to connect to the server at the same time. The EJB specification states that external sockets and multithreading in user defined beans are forbidden. As multithreading and sockets are the only way to deal with concurrent requests from the network, this functionality had to be moved out of the Middleware container and into separated server applications. This means that we get a heterogeneous server application framework, which may not be the best approach for reasons of stability, platform homogeneity and maintenance.

### *3.6.2 End-user Applications*

There are different roles defined for different end-users: farmers, government authorities, veterinarians and consumers. We have not focused on user interfaces for all different groups so far. Based on the EJB application interfaces, we have implemented a simple JSP based management and tracing interface targeted at the farmer. From this interface he can manage the data related to his animals, define trace routines and view log data.

In addition, we have implemented an access point administrator interface that is targeted at system administrators. It basically presents information describing the state of the access points – up time, power state, data logs and current radio tag associations.

# 4. FIELD TRIAL

## 4.1 Test Setup

During the summers 2002 and 2003 we performed field trials to test our system. The main goals of the trials were to test the terminals in the field with respect to performance, battery lifetime and packaging, as well as to test complete system performance.

For the 2002 trial, 50 sheep were equipped with radio tags, and 4 fixed access points were mounted on the mountain and one on the farm, all supporting an 802.11 core network. The mobile access point was not implemented at this stage. The radio tags were fixed to a strap around the neck of the sheep. For the 2003 trial, the number of sheep included was increased to 180, and this time the radio tags were mounted in the ear of the sheep. Also, the mobile access point was included, with a total of four mobile access points mounted in a strap around the sheep's neck. The fixed access points were upgraded to use the GPRS core network.

The test site lies in the Alps of Lyngen, which is a very hostile environment from a technological point of view. Harsh weather combined with a rugged terrain tests the equipment under very difficult, yet real, conditions.

## 4.2 Results and Analysis

### *4.2.1 Technical Performance in General*

In the 2002 trial a lot of the radio tags stopped working due to battery discharge. We believe this is a result of a mix of high loads and consequently a power-drop in the battery, together with varying temperatures. It is well known that batteries perform best under constant load current and temperature; varying temperature and load current will reduce the nominal capacity. We concluded that the battery used in the first version of the radio tag was not suitable due to low current drain capability and too small a voltage rating. Also, the communication range experienced in this trial was shorter than expected, which we traced back to lack of noise suppression in the circuitry. To overcome these problems, we designed a new version of the radio tag, using a more robust battery and focusing on noise problems to improve the communication range. The result was a tag that was almost 50% smaller, yet had almost doubled its communication range. The smaller size made it possible to mount the tags in the ears of the sheep. These new radio tags have performed very well during the 2003 trial, and so far, after six months, we have no indication that any of them has stopped working.

The fixed access points in the 2002 trial had approximately 90% up time during the season, measured using the built-in software for battery supervision. The down periods were due to lack of power supply in long periods without direct sun. However, when the sun was shining, the batteries charged quickly, and the, fixed access points performed very well overall.

However, the first trial showed that fixed access points in the terrain is not a good solution for our system, mainly because the communication range from the access points to the radio tags was too short. The grazing area is too large to be covered by fixed access points, and we only registered a limited number of sheep close enough to the access points. Thus, we focused on the mobile access points for the next field trial in 2003.

Unfortunately, we had a lot of problems with the stability of the mobile access points at the beginning of the 2003 trial. The access point worked for a short period, but then encountered a GPRS connection problem. Due to this, we only had a few registrations from the mobile access points before they stopped working. After collecting the mobile access points, we were able to trace the problem back to a software bug, and when fixed, the access points have been stable and operating properly. However, some of the sheep had come down from the mountain at this point, and the value of the trial was a bit limited. One of the access points also had insufficient encapsulation, resulting in a breakdown due to rough treatment by the sheep carrying it. We still have a problem with the battery for the mobile access point, as it is not dimensioned to support large enough current consumptions, although the capacity should be sufficient.

Encapsulation is another important aspect that we have not addressed in a sufficient manner. Our mobile access points are still too much of a prototype, and the treatment they get during a season mounted on the sheep is very rough and requires a very thorough design and packing. The encapsulation of the radio tag seems to work well, but the mobile access point is more complex, and we need to find a better way of packing it to be able to do service on the terminal when needed.

**Figure 10: Fixed access point and a sheep with radio tag in the test field.**

### *4.2.2 The Mobile Access Point*

Using mobile access points seem to be the correct approach for extending the access net coverage in large areas. They are quite cheap to produce and are an important distributed resource in the network. As the battery technology improves and matures, we believe the mobile access point will play an even more important role, enabling always-on devices, and hence a two-way end-to-end communication to all end-terminals. We have abandoned 802.11 as a core network, but this does not mean that it is a bad approach. In areas without GSM coverage, 802.11 can still be used to extend the network.

Positioning is the most important information of the sheep-tracking application. Today, positioning is done using GPS receivers at the mobile access points. The accuracy of the position is the key criteria. If we use a mobile access point where the UHF communication range is on the order of 150-200 meters, associating each radio tag with the connected access point will probably give sufficient position accuracy. However, we believe that the UHF communication range can be extended to about 800-1000 meters using improved antennas at the mobile access point. If so, the position accuracy of the radio tags will be insufficient. Implementing a more sophisticated positioning scheme, taking into account the connection of one radio tag to several mobile access points, should provide a more accurate position.

### *4.2.3 Battery Lifetime*

Battery lifetime is by far our most difficult problem. The GPS receiver and GPRS modem, which are the most current-consuming parts of the terminal, have been tuned to stay on as little as possible while still providing sufficient position logs and data transfers. The field trials have shown that the nominal capacity of the batteries cannot be expected, mainly because temperature variations and varying current load will reduce the capacity considerably. Our initial guess was that we could use 80% of the nominal battery capacity, but the field trial showed that 50% is a more realistic value. The trade-off between up time and functionality is difficult, but it seems that what we have chosen is adequate for most of our applications. There is no need for the mobile access point to be online all the time, since important events in most cases will be triggered from inside the network, and it is then possible to wake up the necessary equipment to transmit data immediately. However, to squeeze power consumption even further, we probably need to reduce the number of UHF/GPS activities down to two times per day. Theoretically, and according to Figure 4, this will increase the lifetime from 50 days up to 150 days.

### *4.2.4 The Flock Concept*

The concept was initially based on the flock behavior of sheep, and in particular that there will be one flock leader who can carry the mobile access point. However, the trials have revealed that the flock behavior is a bit more complex than we thought. Usually, the sheep stay in groups consisting of mother and a few lambs, and hence, the concept of a few flock leaders and large flocks fails. Different breeds behave differently; some gather in large flocks, our test sheep did not. There are two possible solutions to this, either having a mobile access point on each mother or incorporating a multi-hop protocol to transmit data from the radio tags to the nearest access point. This kind of flooding protocol is also implemented in the ZebraNet project [5]. Using a mobile access point on each mother will be too expensive from the farmer's point of view, hence the flooding mechanism will be a better solution. This will also help when the radio on a mobile access point fails, in which case the data can be directed towards a properly functional mobile access point. Otherwise, failure in the equipment results in loss of data.

### *4.2.5 Benefit to Farmer*

Evaluation of the farmer's benefit has been difficult due to the above-mentioned technical problems and the fact that the user interface has been at a low level. For the farmer to benefit from the system, he needs an easy-to-use interface, preferably with a map showing the position of all flocks and the flock members at the last registration. As explained earlier, we are not at that stage yet, but the user interface has high priority for future work. However, the farmers involved are very enthusiastic, and they clearly express the opinion that this system can be of great help provided they get data presented in a map. They also agree that two reports per day are sufficient.

A weakness of the system is that it doesn't provide position information for sheep that stray away from the flock if, for instance, they are caught by predators or injured in some other way. This can only be provided if sheep have their own mobile access points. However, lack of registration of a sheep is an indication that something is wrong, and the last known position of the sheep can be used as a starting point when searching for it.

## 5. FUTURE WORK

We are currently focusing on two main issues; better positioning schemes and ad hoc routing. In addition, we will focus on end-user applications, with a proper graphical user interface, showing positions on a map. Also, improving power capabilities by adding solar panels to the mobile access point is an issue that has high priority.

### 5.1 Positioning

If the UHF communication has a range of 800-1000 meters, positioning the radio tag by associating it with an access point will not be accurate enough for the sheep-tracking application, and besides, other applications require far better position accuracy than we have today. Positioning small radio tags in ad hoc networks has been a topic that has gained interest from researchers, and some publications have been reported [26] - [30]. The methods used include distance measurements [28], angle of arrival [29], using ultra sound [30], and others [26] [27]. It must be pointed out that positioning in this context adds value only if the range of the communication between radio tag and access point is relatively large.

### 5.2 Ad Hoc Networking

For the sheep-tracking application, we do not need the radio tags to talk to each other, but for other applications, this could add a great value. We are currently focusing on implementing power-aware ad hoc routing protocols where the radio tags can communicate between them using the UHF link. This will be an ad hoc network that, among other things, can be used to extend the communication range by enabling hops, effectively building a communication network of very small, low-power devices. We believe that there are many applications that can use this feature, and there is also a lot of research reported in this area [31] - [36]. For the sheep-tracking project, an ad hoc network combined with a positioning scheme could lead to a reduced need for mobile access points, and hence a total reduction of overall system costs. Also, this will result in different paths back to the access points with the same data possibly registered at several access points. In this way, data loss will be reduced.

### 5.3 Improving Power Capability

The battery capacity is good enough for the access point to last for a few months, but there are applications that require both longer periods of operation and more frequent data capture intervals. Using a small solar panel to charge the batteries is one way to improve the power capability. Today, small solar panels are easily available, and flexible panels can even be used to fit special form factors. We have started a small project to look more closely into this, with particular focus on mounting an access point with a solar panel on reindeer.

### 5.4 Graphical User Interface

So far in the project, we have not focused on the user interfaces, apart from the simple ones described in section 3.6.2. Indeed, for the farmer to benefit from the system, this is of primary concern, and a system that shows the position on a map will be of great value to the farmer when he is out to collect the sheep in the autumn. Today, many maps have been digitized, and this work is still continuing. Given that the map is available digitally, plotting the position is a fairly easy task.

## 6. OTHER APPLICATIONS

As stated earlier, the flock properties of the system are important, and hence, the system can be used for several different applications where flock behavior is a typical feature. In addition, a device like the mobile access point finds many different applications as a stand-alone device.

One application area that benefits from the flock architecture is future home applications, where communication to “things” is becoming a popular research area [23]. Typically, a future home may include devices for communicating to the refrigerator, the oven, the coffee maker, turning on lights, opening doors and lots of other things. Instead of implementing each object with advanced communication equipment, it is possible to use a central communication unit like the mobile access point that communicates to the objects using the UHF band channel described earlier. In this way, the system benefits from a cheap investment. Of course, this also applies to applications in the office environment [24].

Another application area is to use the system on personnel expected to report their positions at regular intervals. This could be a rescue group like police or firefighters, or it could be a military context. Monitoring soldiers is an area of interest. We are planning a field trial in cooperation with the sixth division of the Norwegian army. The primary interest for the army is to get an online overview of the situation for all their units in the field, and an accurate position is a key feature. For the operation-center, this is a key issue for planning, coordinating and regrouping during battle or training. In addition to position, the system can also report the health and stress level of the soldiers (which requires sensors).

Telemedicine is another area of interest. Today, many patients must stay in the hospital or in institutions due to the need for monitoring biometrical data. Many of these patients could be at home if the biometrical data could be monitored remotely. This gives great potential savings for the hospital and it gains convenience for the patient. The ES infrastructure can realize such a system, by integrating different sensors to the radio tag. Some work in this area has been reported in, for example, the TelemediCare project, where the patients use Bluetooth enabled sensors [25].

We have already described the trial application of monitoring sheep in grazing land. Obviously, the system can be used on different animals, and we are already involved in a project that aims at monitoring reindeer with the purpose of preventing them from being run over by trains on the railway. This is a major problem, as each year the train kills hundreds of reindeer in the northern parts of Norway.

## 7. CONCLUSIONS

This paper has described the design of and our experiences with the “Electronic Shepherd” system. The system is developed for low-power, low-bandwidth applications where simple and low-price equipment is important. The system supports flock behavior, which means that it is well suited for applications where a number of objects belonging to a flock can be equipped with low-cost radio communication equipment. These objects communicate to a flock leader that has a global communication channel to the Internet. The technologies implementing the system consist of GPRS, GPS and UHF radio communication.

Considering the system from a network point of view, we have a hybrid radio based network enabling low-bandwidth communications to small objects using a global mobile network as a gateway to the world. This model makes it possible to design low-power, low cost and small size network terminals that can be used in a large scale, to instrument almost any object we wish. The system is based on the presence of mobile access points. These access points act as UHF and GPRS network terminals with UHF network roaming capabilities, implementing a very dynamic mobile network infrastructure. To meet strict terminal power budgets, both mobile access points and UHF terminals are switched on and off at predefined time intervals. This makes outside initiation of real-time data flows difficult; however, it does not pose severe problems as most important events happen on the inside, and such events can trigger a terminal wakeup if needed. All access points are IP enabled, making communication to them simple using well-known protocols.

Two field trials have been performed with promising results. Monitoring sheep out on grazing land is a challenging task that demands a lot from the equipment regarding robustness and power handling. The results from these trials show that there are still improvements that need to be addressed to make the system more stable and reliable, but the concept looks promising. Also, this demonstrates a possible application of the system that originates from real needs of users. Several other application areas have also been identified, and we have started to look more closely into some of them.

Although the ES infrastructure has some limitations as a consequence of intermittent connectivity, we believe that our implementation of prototypes for large scale monitoring of objects makes an important contribution to mobile computing and sensor networks. We also believe that our approach demonstrates an area of applications where the different technologies applied together can have a great impact on users, societies and industries.

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## 9. AUTHORS’ ADDRESS

Telenor R&D, P.O.Box 6593, N-9294 Tromso, Norway

Bjørn Thorstensen
Phone: +47 959 34 044
Mail: bjorn.thorstensen@telenor.com

Tore Syversen
Phone: +47 909 13 338
Mail: tore.syversen@telenor.com

Trond-Are Bjørnvold
Phone: +47 913 50 083
Mail: trond-are.bjornvold@telenor.com

Tron Walseth
Phone: +47 915 77 806
Mail: tron.walseth@telenor.com

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