Advanced Data Communications for Downhole Data Logging and Control Applications in the Oil Industry

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Abstract. We present details of ‘Mercury’, a high-speed downhole communications system that utilizes the (metallic) wall of a gas or oil pipeline or a drill ‘string’ as the communications ‘channel’ to control or monitor equipment or sensors used in the oil industry. Conventional downhole communication systems typically use ‘mud pulse’ telemetry for ‘Measurement While Drilling’ (MWD) operations. Current mud pulse telemetry technology offers bandwidths of up to 40 bit/s. However the data rate drops with increasing length of the wellbore and is typically as low as 1.5 bit/s - 3.0 bit/s at a depth of 35,000 ft - 40,000 ft. The system described, by contrast, offers data rates of several megabits per second over distances of many kilometres and uses Orthogonal Frequency Division Multiplexing (OFDM) coupled with Wideband Frequency Division Multiple Access (W-CDMA). This paper presents details of our system; results of several trials undertaken on actual gas pipelines in the United Kingdom will be presented at the Conference.

Keywords: Downhole communications, MWD, OFDM, DSSS, W-CDMA, FPGA.

1. Introduction
Harsh communications environments, such as those encountered in downhole applications, present special challenges for improving data transmission technology and have precluded the use of existing techniques. Some solutions have explored pulsed communication through fluids and inductive coupled communication between drilling pipes. Pulsed communication has the drawback of a long delay between the sending and receiving of data and inductive coupled pipes suffer from loss of data integrity and signal strength in the past.

Mercury is a high-speed downhole communications system that utilizes the (metallic) wall of the pipe as the communications channel. It has been recently demonstrated in a series of tests and trials – at the Theddlethorpe Gas Refinery, near the Lincolnshire Coast in England, at the Montrose RGIT training well in Scotland and in an extended six-week trial between the St Fergus and Cruden Bay gas terminals, also in Scotland, during which time communication speeds of several megabits per second were consistently achieved.

Mercury uses a combination of two modulation techniques to handle the downhole environment. To combat multipath, where signals are reflected from discontinuities in the electrical impedance of the
pipe and so multiple ‘echoes’ of the signal arrive at the receiver, Mercury uses Orthogonal Frequency
Division Multiplexing (OFDM) [1]. In OFDM the communications bandwidth is subdivided into
many parallel sub-channels. In Mercury there can be as many as 1024 parallel frequency channels. In
addition Mercury uses Wideband Frequency Division Multiple Access (W-CDMA) [2], a form of
Direct Sequence Spread Spectrum (DSSS) [3] modulation that allows it to dynamically adapt to
changing channel conditions and to trade off data rate for signal-to-noise ratio (SNR), as well as to
accommodate multiple downhole sensors or equipment.

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Orthogonal Frequency Division Multiplexing (OFDM) is a method of transmitting data over a range
of frequency bands. The main principle of OFDM is that it has a set of sub-carriers within one
particular frequency range. This main feature is exploited by making the adjacent sub-carriers
orthogonal to each other. This produces two main benefits: The first is that the symbol period is
increased, as each sub carrier holds only one symbol; this means that the length of the whole frame is
in fact the length of the symbol, thus reducing inter-symbol interference (ISI). The other main
advantage is that the guard interval, that is typically used to protect frequencies from interfering with
each other, can be removed as a result of the orthogonal properties of the carriers. This means that
OFDM can produce data rates close to the Nyquist rate and is thus seen to be a highly efficient means
of data transmission.

Processing is carried out using a specially designed miniature low-power processor card that contains
an Atmel 32-bit microcontroller, RAM, Flash memory and an FPGA (that undertakes all the intensive
DSP operations required for the OFDM and W-CDMA signal processing) [5]. A bespoke version of
an open source real-time operating system (RTOS) is used and programming is carried out using Keil
C for the microcontroller and a version of VHDL for the FPGA.

Without the use of the FPGA, it would not be possible for Mercury to carry out the compute-intensive
signal processing operations needed to process the OFDM and CDMA protocols in real time. Fast
Fourier Transforms (FFTs) of data sets comprising several thousand elements are required at the
channel symbol rate. An FPGA is ideally suited to performing operations that are inherently parallel
in nature – such as the FFT – while the serial nature of computations carried out by a conventional
microcontrollers mitigate against their use in such environments. The entire FPGA processing was
simulated using the well-known mathematical software, MATLAB® using the Xilinx® FPGA System Generator and HDL (Hardware Description Language) Coder.

2. THE PIPELINE COMMUNICATIONS CHANNEL

2.1. Ideal and Real Communications Channels

An ‘ideal’ communications channel would pass all electrical signals of any frequency or amplitude without attenuating them and without adding noise or interference. Clearly such channels do not exist. In practice all communications channels attenuate signals and typically attenuate higher frequency signals to a greater extent than lower frequency signals. In addition, all communications channels add noise and, unless the channel is a theoretical model known as a transmission line, will reflect some of the signal, propagating from the transmitter to the receiver, back towards the transmitter. This effect results from ‘discontinuities’ in the electrical characteristics of the communications channel between the transmitter and receiver. It is these discontinuities that cause the propagating signal to be partially reflected back towards the transmitter.

In addition – and sometimes, but not always, as a consequence of the previous effect – most communication channels contain multiple physical paths between the transmitter and the receiver and, as a result, multiple copies (‘echoes’) of the transmitted signal will arrive at the receiver. This is known as ‘multipath propagation’.

Multipath propagation is a common occurrence in digital communications and there are several ways in which it can be tackled. Relatively recently a modulation scheme known as OFDM – or orthogonal frequency division multiplexing – has been developed that is particularly resistant to the effects of multipath. OFDM is used in the Digital Audio Broadcasting (DAB) standard for digital radio [6].

We might expect the characteristics of a pipeline to be subject to considerable electrical discontinuities – causing multiple reflections and re-reflections – as well as multipath. Such electrical discontinuities would be likely to originate from the various joints, welds, valves, and junctions etc. that make up a typical pipe. As a result, OFDM might be expected to be the ‘protocol of choice’ for such a system, since it would seem to offer the best chance of combating these effects.

A further problem such a system faces – over and above those that have been discussed already – is that, in the case of MWD [4], the channel characteristics are not constant and change with time. This is a result of sensors and actuators moving, thus causing the length of pipe or drill string over which the signals have to propagate to vary. One might logically expect that, the further away from the transmitter such a system moves, the poorer the ‘quality’ of the channel will become.

There are several solutions to this problem. We could design the communications modulation scheme and protocols (including the error handling) to deal with the ‘worst-case scenario’. But this inevitably implies that, when conditions are benign, we are operating in a sub-optimum environment because we have reduced the effective data rate to be below the Channel Capacity to ensure that all data arrive correctly.

A more intelligent approach would be to try to find a way in which we are able to change the operation of the communications system to dynamically adapt to the varying communications channel conditions. We need to find a way to modify the communications modulation scheme, protocols and/or error handling to reduce the effective data rate to below the channel capacity.

In Mercury CDMA provides the dynamic response to changing channel conditions; OFDM provides the resistance to multipath. CDMA employs a modulation technique known as ‘Spread Spectrum’, which allows us to dynamically ‘trade off’ the rate of data transmission with the channel characteristics. The first author has worked in the field of spread spectrum for many years and has many publications and patents in this area.
2.2. Measuring the channel characteristics

In order to understand the electrical characteristics of a typical gas pipeline, tests were carried out at the Conoco Theddlethorpe gas refinery, which is situated in the south of the UK. We wanted to understand how the electrical characteristics of the pipeline vary with distance. This information can be used to select the parameters for implementing the CDMA part of the modulation scheme. At Theddlethorpe we had access to a 50km length of active gas pipeline, between the Theddlethorpe gas terminal and the Humber Refinery, that was buried, but where cathodic anti-corrosion access points were available at frequent intervals along its length. Figure 2, below, shows the transmit antenna being attached to the Humber Oil Refinery Export Line, which carries condensate from Theddlethorpe the 50 km to the Humber Oil Refinery.

In the trials at Theddlethorpe, the propagation characteristics were measured from antennas attached to the outside of the pipeline. For many other situations however, such as MWD, the equipment would be communicating to actuators or sensors contained within the well-bore itself. To facilitate the measurement of channel characteristics for such situations, a separate set of trials was carried out at the RGIT Training Well installation, near Montrose in Northern Scotland. This installation is used for training oil workers and forms a part of the necessary certification that anyone working in the oil industry – either on-shore or off-shore – needs to have. The well that we had access to was shallow by oil industry standards (2500'), but it provided a safe and flexible and, more importantly, non-production environment in which we were able to carry out extensive measurements.

A picture of the RGIT Montrose installation is shown below in Figure 3. The downhole module was enclosed in a stainless-steel pressure housing and was lowered down the well bore in increments of 50 ft. using an isolated wireline [7]. At each location the data rate, BER, SNR etc. were measured and logged using a commercial data logger at the surface connected to the topside transmit/receive module. At the well bottom, the downhole module was detached from the wireline, which was retrieved, in order to guard against the possibility that the wireline itself was acting as a conduit for the signals.
3. THE ST. FERGUS TO CRUDEN BAY TRIALS

3.1. Overview

3.1.1. Introduction

Figure 4 shows an aerial view of the St. Fergus Gas Terminal, as well as a schematic illustrating the relative positions of St. Fergus Gas Terminal, the Cruden Bay Gas Terminal and their interconnect to the North Sea oil fields. The equipment at both locations was also connected by high-speed mobile Internet to the project offices in Aberdeen, also in Northern Scotland. This allowed the experiment to be controlled and monitored remotely and for statistical data, illustrating the real-time performance of the pipeline communications network between the two gas terminals, to be observed. This was necessary because access to the gas terminals is strictly limited to authorized personnel and frequent visits, to reconfigure the equipment or collect data, were not practical.

3.1.2. The St. Fergus to Cruden Bay Trial

For the benefit of the project sponsors, these data were also made available in real-time on a dedicated web server, allowing them to ‘log in’ at will and note the key current network performance parameters – such as data rate, BER (bit error rate), SNR (signal-to-noise ratio) etc. The experiment ran continuously for a six-week period at which point it was terminated due to operational reasons.

Processing at both St. Fergus and Cruden Bay was performed using the bespoke processor board mentioned earlier, comprising the Atmel 32-bit processor and FPGA. A secondary processor card was employed as a dedicated interface to the 3G cellular data modems as well as to control the main Mercury processor card, consolidate and analyze the received data and to receive, interpret and implement commands sent over the cellular modem. Both installations – at St. Fergus and at Cruden Bay – were encased in ATEX approved enclosures. Since July 1st 2003 it has been mandatory under European law that all equipment for use in a potentially explosive atmosphere must conform to specific safety standards. An ATEX enclosure (from the French “ATmosphère EXplosible”) provides
the necessary protection for electrical equipment operating in such an environment. Since both St.
Fergus and Cruden Bay are operational gas terminals, compliance with ATEX Directive 94/9/EC is
mandatory.

During the trial, data rates of between 5 and 8 megabits per second were consistently observed and
large files of data were repeatedly transferred back and forth to simulate the retrieval of data from
pipeline sensors and the control of downhole actuators. Comprehensive statistical data were gathered
for subsequent analysis and to guide the future ‘tuning’ of system parameters. These will be presented
at the conference.

Although both the St. Fergus and Cruden Bay terminals are subject to significant EMI
(electromagnetic interference), as a result of the extensive electrical machinery operating in both
locations, no adverse effects were noticed during the six-week trial and there appeared to be no
occurrence of diurnal or other periodic effects, as electrical machinery was switched on and off.

![Figure 4](image-url)

Figure 4 – An aerial view of the St. Fergus Gas Terminal in Northern Scotland and a schematic
showing the interconnect

4. CONCLUSION

In this paper, we have described a downhole communications system that uses advanced
communications protocols and the metallic drill string or pipe wall, to achieve data rates far in excess
of those achieved using conventional techniques – such as mud-pulse telemetry. Comprehensive tests
were undertaken to characterize the electrical characteristics of the pipe and drill strings at the
Theddlethorpe Gas Refinery and the RGIT Training Well. A six-week trial between the St. Fergus and
Cruden Bay Gas Terminals in Northern Scotland, consistently produced data rates of between 5 and 8
megabits per second. Further details of the communications protocols and results obtained will be
presented during the conference. It is hoped to deploy the system in operational environments in the
near future.

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