VERY HIGH-SPEED DRILL STRING COMMUNICATIONS NETWORK

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ABSTRACT

A history and project summary of the development of a very high-speed drill string communications network are given. The summary includes laboratory and field test results, including recent successes of the system in wells in Oklahoma. A brief explanation of commercialization plans is included. The primary conclusion for this work is that a high data rate communications system can be made sufficiently robust, reliable, and transparent to the end user to be successfully deployed in a down-hole drilling environment. A secondary conclusion is that a networking system with user data bandwidth of at least 1 million bits per second can be built to service any practical depth of well using multiple repeaters (Links), with spacing between the Links of at least 1000 ft.

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GRANT DE-FC26-01NT41229

BACKGROUND

Overall project objectives & scope

Novatek and the U.S. Department of Energy have engaged in Cooperative Agreement DE-FC26-01NT41229 to develop a robust high data rate communications system for the down-hole drilling environment. "High data rate" in this context means approximately 1 million bits/sec of transmitted data. By comparison, conventional uncompressed data transmission speeds using mud pulse telemetry reach approximately 8 bits/sec.

The intended value of this new data service derives from:

1. Providing high-resolution downhole drilling information to the surface to enable fully-informed drilling decisions to be made in real time.
2. Providing real-time control of downhole tools and instrumentation to improve the responsiveness and intelligence of these devices and to improve the safety of the drilling process.

The ultimate objective of the technology is to enable substantial improvement in overall field productivity by helping drillers to locate subsurface resources more precisely and to safely position a wellbore in the sweet spot of the reservoir.

Planned development activities over the course of the cooperative agreement have included optimization of a novel means of transmitting data through threaded drill string components and construction and demonstration of the technology in a full-size high-speed transmission line. Also included within the scope of the project has been the development of suitable electronic components to demonstrate a drilling data network and to demonstrate connectivity of the system with a third-party downhole measurement tool.

Development history

The overall concept for this work is rooted in and leveraged from Novatek's work with the U.S. Department of Energy in development of a smart integrated hammer-based drilling system (cooperative agreement number DE-FC26-97FT34365). During the course of this earlier project, the basic concept of a distributed data network was developed and disclosed to the DOE and the industry.[i,ii] This original concept recognized the desirability of having multiple electronic repeaters deployed in the drill string for enabling high-speed data transmission. The 30 June 1998 status report stated, "Instead of relying on sending a high-energy, relatively low-frequency signal the entire length of the string, this concept allows a low-energy, high-frequency signal to be sent via a miniature, low-cost repeater at each tool joint. … The signal is then cleaned up (conditioned) by circuitry embedded within the ring, powered by small batteries also contained within the ring, and then sent on up the next length of pipe by the pin coupler.” [i]

The largest challenge confronting this concept was the development of a suitably robust transmission line in drill pipe. As far back as 1939, technology had been proposed to provide a way of transmitting data from down-hole drilling tools to the surface. The stumbling block in most instances was bridging the tool joints that connect segments of drill pipe. Commercialization of such data transmission systems has been prevented by corrosion, shorting, and other damage to electrical connections at the hundreds of tool joints present in a typical well, by interference of system operations with rig floor operations, and by unreliability of the system.

Initial development efforts carried out by Novatek (under cooperative agreement -34365) focused on the use of acoustic transmissions to carry high frequency data through a single length of *unwired* drill pipe. Data rate limitations attending this first approach motivated a second concept for a telemetry system that utilized wiring in the pipe, but that transmitted data through the tool joints using high frequency acoustic transducers (see **Figure 1**). However, difficulties related to implementation of the acoustic transmitters led Novatek to seek other means of transmitting across the joint. Fundamental work performed with an inductive coupling system returned promising results, which caused all development effort to shift to the present concept of a wired pipe with inductive couplers at each end.

Figure 1. *Acoustic Transducer used in early development efforts*

The DOE’s substantial interest in Novatek’s latter approach led in 2001 to a funding partnership between Novatek and the DOE specific to the development of the telemetry system; this project concluded at the end of 2004. DOE’s Strategic Center for Natural Gas and DOE’s National Petroleum Technology Office, both part of the National Energy Technology Laboratory (NETL), have each provided partial funding for the project through the two cooperative research agreements.

Project plan

Development of the high data rate communications system under cooperative agreement -41229 was divided into three phases, which provided for progress review, feasibility assessment, and confirmation or redirection of focus at each stage prior to commitment of further resources to the project. Each successive phase built upon successes of previous phases, including increases in the complexity and robustness of the transmission line and increases in the sophistication and scale of testing (e.g., moving from laboratory tests through full string field testing). Technical success was measured by the ability of the system to transmit information faithfully through the indicated drill string components for the duration of the testing. Probable commercial success was assessed from the perceived level of commitment from potential industry partners or licensees, by successful reduction of manufacturing costs and complexity, and by development of positive and realistic financial models.

Phase I began in 2001 and had as its objectives to:

a) optimize the novel transmission line for passive transmission range and handling robustness
b) develop economic means of placing and protecting a data cable within drill pipe
c) demonstrate communication through a short (scaled) drill string under drilling conditions
d) develop design concepts for expanding the technology to specialty down-hole tools, such as drilling jars and motors.

Phase II commenced in 2002 and included the building and field testing of full-scale drilling tubulars. The objectives pursued during this phase were to:

e) improve the coupler to attain at least 1000 ft passive range and minimize manufacturing variations
f) demonstrate the robustness of full-scale transmission line components under "typical" field handling conditions
g) extend implementation of the transmission line to heavyweight drill pipe, drill collars, downhole motors, drilling jars, and a 3rd party tool
h) demonstrate operation of a bi-directional network in a 6,000 ft drill string under field drilling conditions

Phase III work began in 2003 and continued through 2004. Objectives of this phase were to:

i) complete wiring of all essential drillstring elements and demonstrate a top-to-bottom transmission line in a field application
j) demonstrate the utility of the transmission line with a third party tool and expand the number of tools that are capable of interfacing with the network
k) continue improvements to the system, particularly in the area of improved handling robustness, increased pressure and temperature capability, and improved transmission range.

In the sections following, the system resulting from project is described, together with the experimental methods utilized and the results obtained from testing of the system. In addition, conclusions are drawn about the technical and commercial value of the technology .

SYSTEM DESCRIPTION

The down-hole network concept

The general concept for a down-hole high data rate communications system pursued in this work is shown in

Figure 2. The system consists of active and passive electronic components that provide high speed two-way communication between a top-hole server computer (master) and a number of

intelligent down-hole or surface components. The passive portion of the system includes wired drill pipe, drill collars, drilling jars, reamers, motors etc. This set of components comprises the *transmission line* portion of the network. Active components of the network are primarily responsible for generating useful data, responding to commands from the surface, and establishing orderly communications on the transmission line. Such components include network electronics and measurement and logging tools (MWD, LWD), drilling tools, seismic tools, network electronics, etc. that are interfaced with the network electronics.

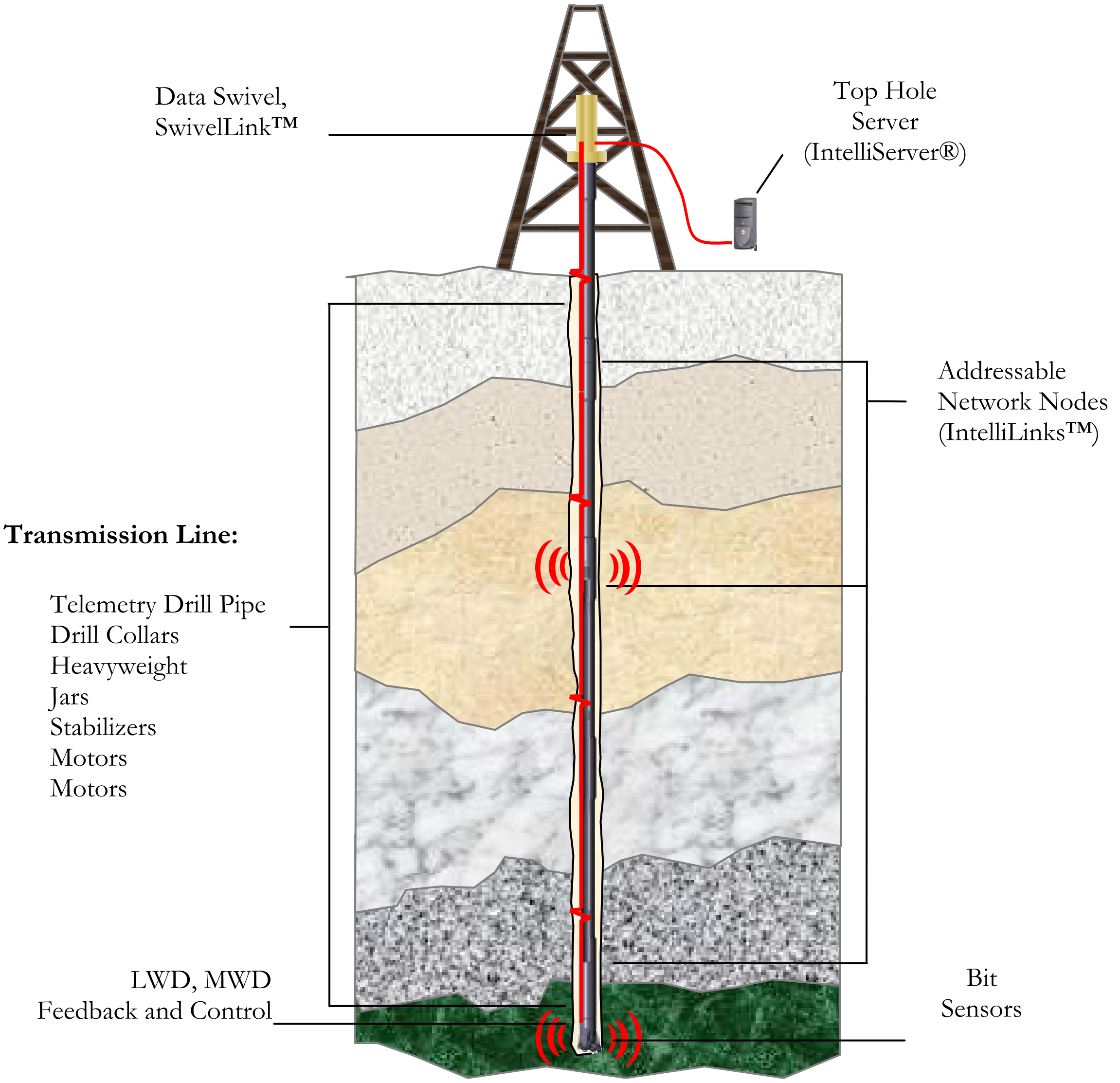

Figure 2. *IntelliServ® Network Concept*

The system as a whole is now known as the IntelliServ® network. In the IntelliServ network, the flow of high-speed data occurs *along* the transmission line and *between* the top hole server and active components (addressable network nodes or Links™). The IntelliServ system provides a true network environment so that active components may be distributed anywhere along the transmission line. A device called the data swivel is placed at the top of the string to facilitate transmission of data from the rotating drill string to the stationary world. A more detailed description of this essential networking equipment follows.

IntelliServer® (Top hole server)

The top hole server or "IntelliServer" is the network controller or "master" for the IntelliServ network. Located in the doghouse or elsewhere near the drill rig, the IntelliServer controls the flow of data between the various downhole and surface sources and destinations. The IntelliServer further converts data between the proprietary IntelliServ networking standard (which is needed to transmit the data over the unique drill pipe transmission line) and standard serial or Ethernet packets that can be utilized by a Windows or UNIX computer located in a network at the surface. The top hole server also functions as a master timekeeper for time-synchronous applications and logs statistics about the utilization of the IntelliServ network.

Figure 3 shows the present version of the IntelliServer. The hardware includes a stack of electronic devices including a personal computer, disk storage, a battery backup, and several ports that allow connection between the IntelliServ network and the outside world. Multiple users can connect to the IntelliServer and simultaneously communicate with down hole (or surface) tools.

Functionally, the IntelliServer keeps all of the various tools and devices organized on the network by giving each a unique address to which information may be routed. Thus, when a user wishes to communicate with a particular tool, he may issue a command to a certain device address from his application computer (which also has a unique address). Prior to being sent to the destination device, commands or data packets from the user's application are "wrapped" up by the IntelliServer into an IntelliServ network packet. Once successfully transmitted, they are unwrapped by the downhole IntelliLink and delivered to their destination, thus maintaining the original form of the packets sent by the application software. Down hole tools must attach to the network through IntelliServ's IntelliLink™ modules (see below).

***Figure 3**. IntelliServer*

The wrapping and unwrapping is transparent to the end user and preserves protocols, security encryptions, and commands specific to a particular user's application software. Because communication through the IntelliServer is transparent, the customer attaching to the IntelliServer does not need to understand the internal workings of the network in order to connect to the data service; similarly, IntelliServ can provide the data service without needing to understand specific communications protocols that may be proprietary to a particular tool vendor.

IntelliLinks™

IntelliLinks (or simply "Links™") are key to the functioning of the IntelliServ network. The inevitable loss of signal quality in any transmission line requires restoration of signal strength and data integrity after some characteristic transmission distance. As the desired data rates across the transmission line increase, the characteristic distance decreases. The characteristic distance may be also be affected by environmental conditions such as down-hole temperature. Accordingly, Links are placed in the IntelliServ transmission line to boost restore signal strength and integrity. Any number of Links can be deployed, providing for unlimited length of the transmission line.

Links are themselves intelligent downhole tools. Not only do they restore signal strength and integrity, but they may also gather and transmit data, receive and respond to data from the IntelliServer, and provide an interface port for third party down-hole tools. They thus become the eyes, ears, and mouth of the network. Since they may be deployed anywhere within the drill string, they enable communication with mid-string components while drilling. Mid-string links are especially important for drill string dynamic studies, seismic studies, and for safety – for instance, for detecting and tracking a pressure kick. Links may be deployed as standalone tools, or the Link electronics may be embedded inside a third party tool.

Full-Length IntelliLinks™. The standalone IntelliLink is designed to behave and handle like a regular joint of drill pipe and may be inserted anywhere in the drill string. It includes a shortened pipe section that has a nominal length of 28 ft and a 4-ft Link sub which, when assembled, is consistent in length with standard range 2 drill pipe. The shortened pipe section of the IntelliLink assembly may be a normal weight pipe, heavy weight pipe, or a drill collar, depending on where in the string the Link is deployed. In each case, the bore of the Link assembly is the same or nearly the same as the standard minimum bore through the tool joint. Thus, in most cases the Link assembly does not pose significant additional restriction on the drift of the pipe. The IntelliLink sub is located on the pin end of the assembly, so that the assembly looks like a standard pipe, except that it has an elongated pin tool joint. This construction allows the assembly to hang in the slips like a normal joint of drill pipe.

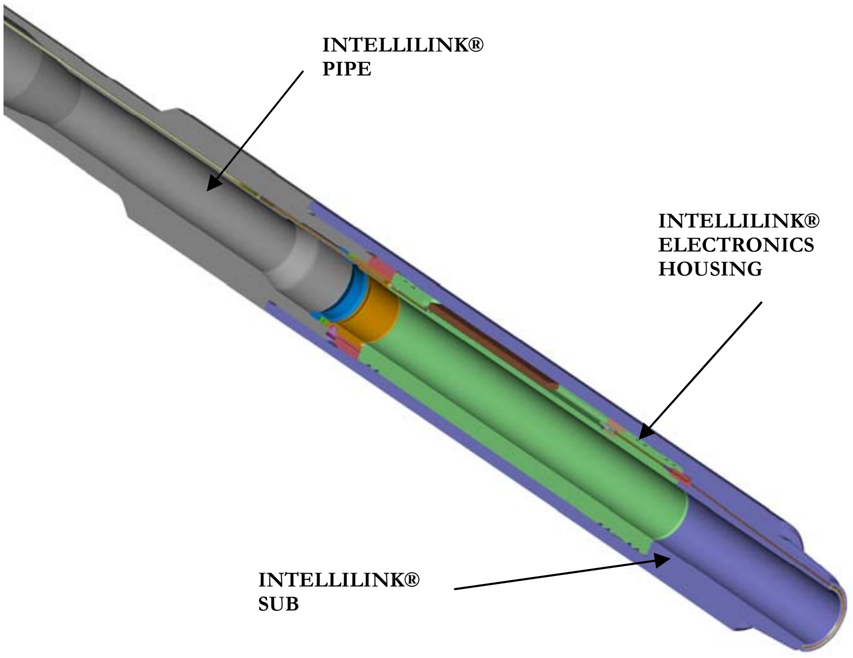

Figure 4. *Full-Length IntelliLink™*

Figure 4 shows a cross sectional view of the standalone IntelliLink. The Link electronics housing is located inside the pin-end sub. This electronics housing is a pressure vessel that protects the electronic circuitry of the Link from the downhole high pressure environment. It contains the circuit boards, sensors, and batteries required to provide the functions mentioned above. Traditionally, MWD and LWD assemblies have been deployed only in the bottom-hole assembly (BHA), where the ID of the tubulars is reduced and there is plenty of room for batteries and circuit boards. The design of Link subs for mid-string deployment, where the ID of the tubulars is larger, has presented new design challenges, because provision for adequate longitudinal and torsional strength and for resistance to downhole pressures restricts the space available for batteries and electronics.

SwivelLinks™. The SwivelLink is a Link that is mounted near the top of the drillstring, either just below the top drive or just above the kelly, depending on the type of drill rig used. Its function is to transmit data from the surface components of the network to the drillstring components and vice versa. It effectively isolates all surface cabling from the downhole system. This enables a greater number of pipes to be added between the SwivelLink and the nearest downhole link than would otherwise be possible, which thereby increases the spacing between all downhole links. The SwivelLink isolates downhole components from surface electrical noise and provides a large signal-to-noise ratio for the surface transmissions. The simplest embodiment of the SwivelLink includes a cable that connects surface and downhole components. Alternatively the surface link may utilize wireless or infrared technology to simplify surface wiring and eliminate the rotary data connection.

Data Swivel

The IntelliServ data swivel is the uppermost transmission line component in the drill string. It is the data interface between rotating and stationary worlds and is therefore comprised of a rotating and a stationary assembly. The data swivel itself is a passive component – data is transmitted across its rotating interface using an inductive coupler (see discussion below). However, it is often coupled with a SwivelLink, which is an active component that boosts signal strength at the data swivel.

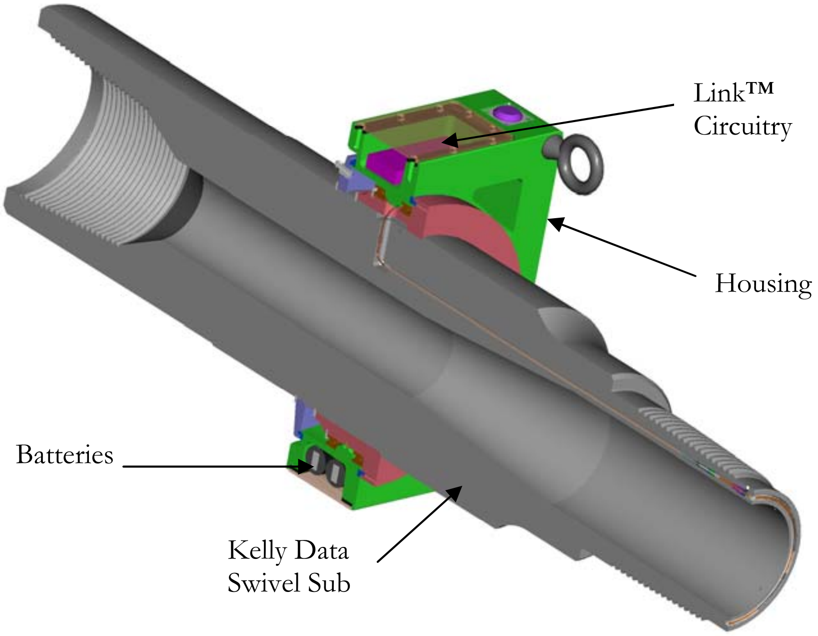

Figure 5. *SwivelLink™*

Figure 5 shows a SwivelLink configured for a kelly. Circuitry and batteries are in a protective housing The SwivelLink may reside on either side of the rotary couple; but to ensure best noise immunity, the preferred location is on the rotating part of the data swivel,. At present, for simplicity, the SwivelLink is attached to the stationary assembly. The stationary assembly is connected to the IntelliServer via a shielded data cable. Future designs of the data swivel could include coupling through radio signals or infrared, or direct electrical coupling through slip rings or a mercury connector. In the case of the radio or infrared designs, the radio/infrared transmitter could be attached to the rotating or stationary part of the data swivel. In either case, the receiver could be placed at a convenient location on or off the rig floor.

A rotary transformer comprised of a stationary ring and a coupler ring insert is incorporated into the present data swivel, as shown in **Figure 6**. This rotary transformer ensures a low noise transfer of the signal as the body of the data swivel rotates with respect to the derrick. Other components include two radial bearings for rotational longevity and two rod wipers and a shield for protection from the elements and from foreign objects. Note that the pin end of the data swivel is the joint in the system that sees the greatest number of makes and breaks. This function is nomally performed by a kelly (or top drive) "saver sub".

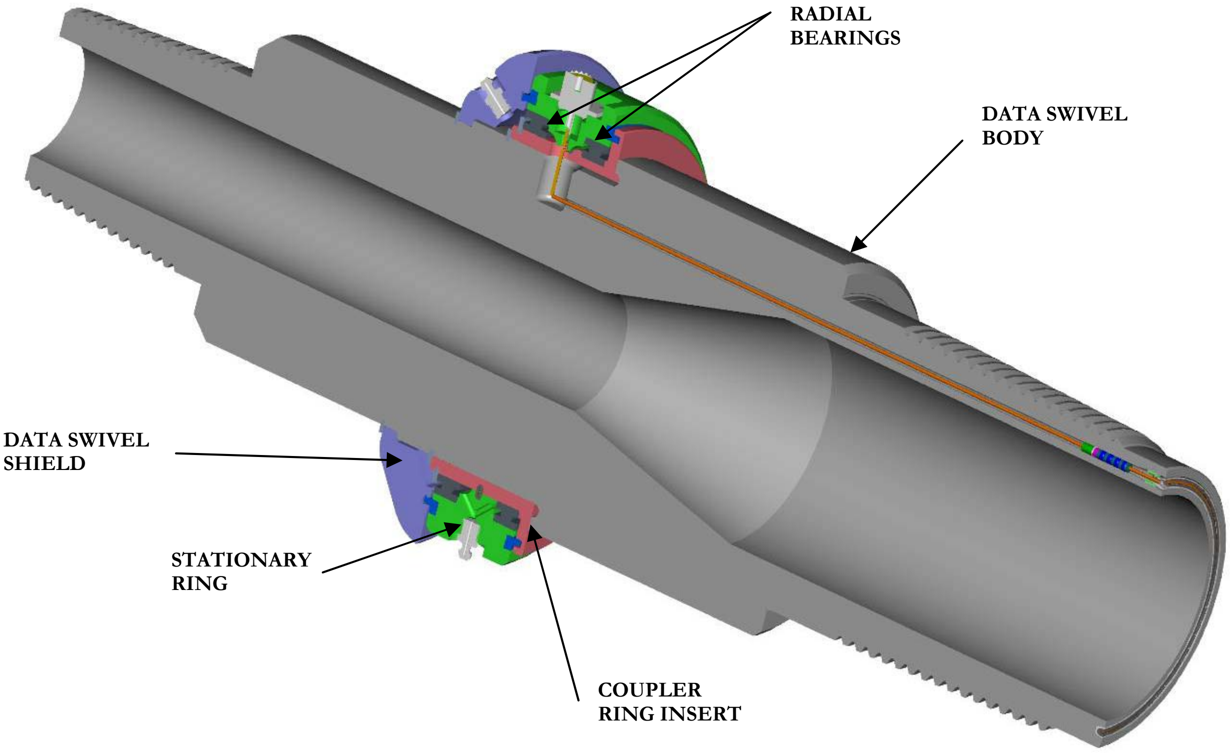

Figure 6*. Data Swivel*

Transmission Line Components

The backbone of the IntelliServ network is its transmission line, comprising wired drill pipe, heavyweight drill pipe, drill collars, drilling jars, stabilizers, reamers, motors, etc.

Basic "milli-hop" technology and IntelliPipe®. The simplest and most effective engineered data path is a continuous cable. However, use of segmented drill pipe requires means to accommodate the continual addition of pipe segments. In the drilling environment, robustness under handling and operating conditions is essential, and interference with rig floor procedure and the resulting non-productive time must be avoided if the system is to accepted. The IntelliServ network satisfies these requirements with a segmented engineered data cable wherein neighboring pipe segments are coupled at each end via a high efficiency, low power, "milli-hop" transmitter. This transmitter creates a robust data path across the threaded drill pipe connection to the adjacent segment. Electrical coupling is automatic as each tool joint is made up. Because this wired pipe requires no special handling,[1] standard rig floor procedure is preserved.

The milli-hop transmitter utilizes closely-coupled inductive coils (IntelliCoils™) with magnetic field containment strategies to passively transfer a modulated radio frequency carrier across a very small gap with high efficiency. This results in a very low-power system. This design allows the IntelliCoils to be sealed and protected against the harsh drilling environment and thereby adds substantial robustness to the system. An inductive system is quite insensitive to handling conditions, since electromagnetic waves can pass with impunity through pipe dope, drilling mud, and grime.

Figure 7 schematically depicts the flow of data through milli-hop transmitters in adjacent pipes . The IntelliCoil couplers are mounted in a protective groove that is machined in the secondary shoulder of a double shouldered tool joint (see Figure 8). Pipe that is thus wired is called IntelliPipe®. The two key transmission line components of IntelliPipe are a high-speed data cable and a set of IntelliCoils that inductively couple adjacent drill pipes as they are added to the drill string.

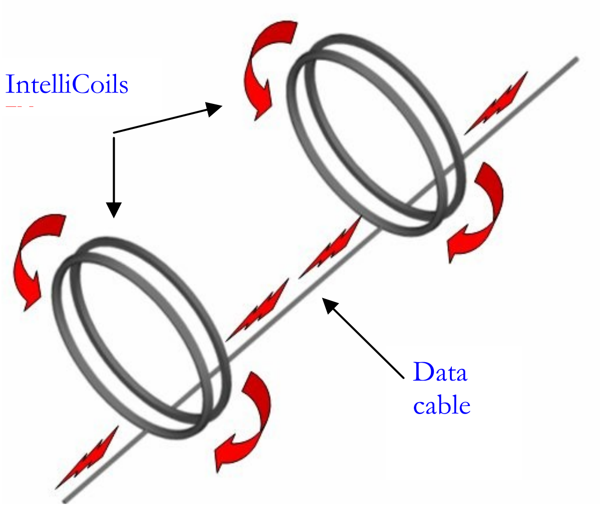

Figure 7. *Schematic flow of data in IntelliServ® transmission line components*

High speed data cable – IntelliCoax™. The most efficient way to transmit data over the IntelliServ® network is with coaxial cable. The characteristic impedance of this cable may be chosen to give the best match for a given IntelliCoil design.

The cable is prepared for downhole use by swaging it into a thick-walled stainless steel conduit, so that the cable and its armor become an integral unitary assembly (called IntelliCoax™). The conduit provides support and protection to the cable and makes it particularly adaptable to pressure, tensile, and flexural loads that are experienced by drill pipe and other wired down-hole equipment such as drilling jars and motors. The outside diameter and wall thickness of the tube are set by mechanical constraints, mainly by the amount of room available for fixing the cable inside the tool joint of the drill pipe and by the resistance of the conduit to collapse under external pressure.

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[1] *On-shore field tests have introduced one non-standard procedure -- the application of pin nose protectors to the bottom of each stand as it is racked back. This has been shown to incur no non-productive time and has been readily accepted by drillers, who see its advantage in protecting both the electrical and mechanical integrity of the pipe. For offshore applications, which are more highly automated, pin nose protectors will not be necessary.*

Figure 8 illustrates how each end of the armored high speed data cable is housed in a small-diameter hole that is gun-drilled in the wall of the IntelliPipe tool joints. Note that the cable breaks out into the internal upset region of the pipe and then travels along the inside diameter of the drill pipe, where it is exposed to drilling mud and to any tools that may travel inside the pipe. This region of the cable may be further protected (if needed) by installation of a metal liner inside the pipe, which is formed in place by hydroforming or other suitable metal forming technology. Alternatively, the cable may be affixed to the wall using clips that are either integral with the pipe wall or attached thereto. Whether or not a liner or clips are installed, the cable is held mechanically inside the pipe by stretching the cable taut with approximately 500 lbs of preload and by anchoring each end of the cable inside an enlarged portion of the gun drilled hole. This preload allows for reversed bending of the drill pipe without ever placing the cable under compressive loads, thereby preventing buckling of the cable.

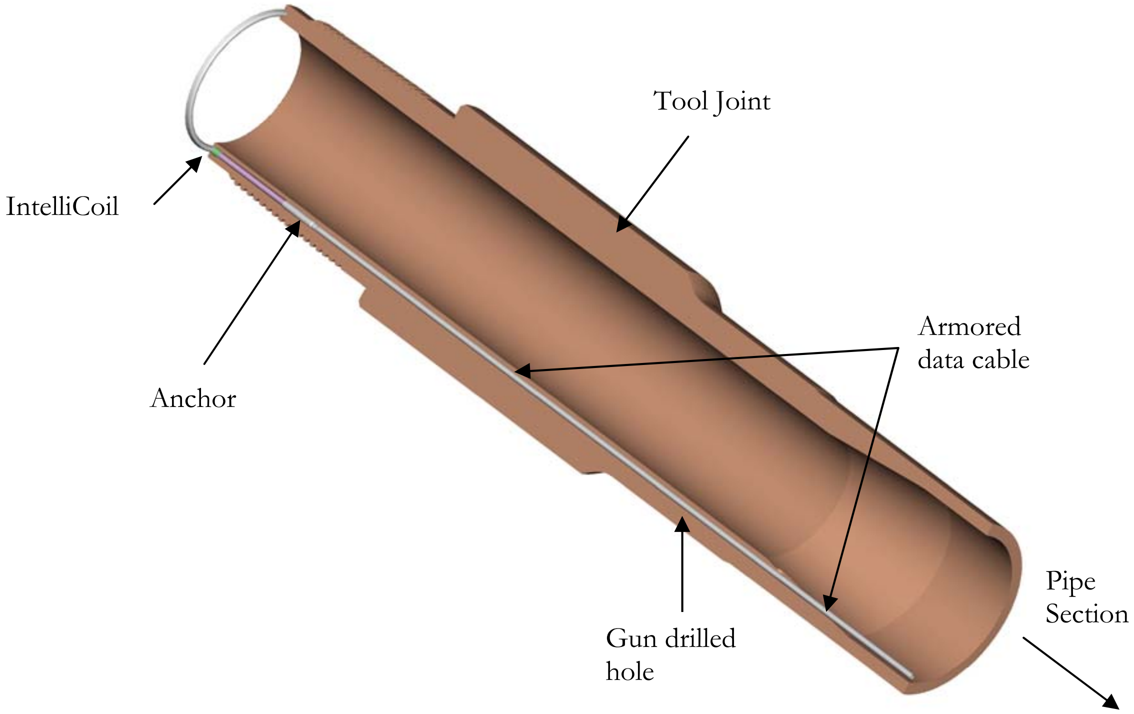


Figure 8. *Placement of high speed data cable inside a tool joint*

The cable is anchored inside the pipe by flaring each end of the steel conduit into which the cable is swaged such that the cable cannot pull out of either tool joint. The anchoring mechanism is a two-staged flaring mandrel or "flarel" that has been optimized to provide an anchoring force that is equal to the strength of the conduit itself. The conduit (and therefore the anchor) is strong enough to accommodate strains in the pipe that are equal to the yield strain of the pipe.

Figure 9 shows the flaring mandrels that anchor the cable inside the tool joint. The flaring mandrels are also designed to form a smooth, survace with a precise inside diameter in the flared end of the conduit. The IntelliCoil™ coupler is subsequently assembled into the flared end and seals against its inner surface. This tight tolerance enables the seals to function reliably at the highest anticipated downhole pressures and temperatures.

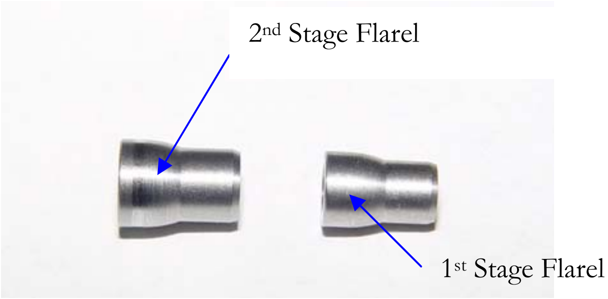


Figure 9. *Flaring mandrels for anchoring cable in pipe*

IntelliCoil™ coupling system. The IntelliCoil non-contact coupling system comprises two mating half-transformer rings. A cross section of this coupler is shown in **Figure 10**. The key to efficient transmission of the radio frequency signal across the joint is to tightly couple the adjacent coils with a U-shaped non-dissipative material, namely ferrite. Ferrite is an iron oxide ceramic with additions of manganese oxide, zinc oxide, or other minor constituents. It is electrically insulating but magnetically conductive. Ferrite is brittle and difficult to machine in large shapes. However, because the magnetic field curls around the adjacent coils in a plane perpendicular to the conductors, and not in the plane of the coils, only a short magnetic path that wraps around the adjacent coils is required.

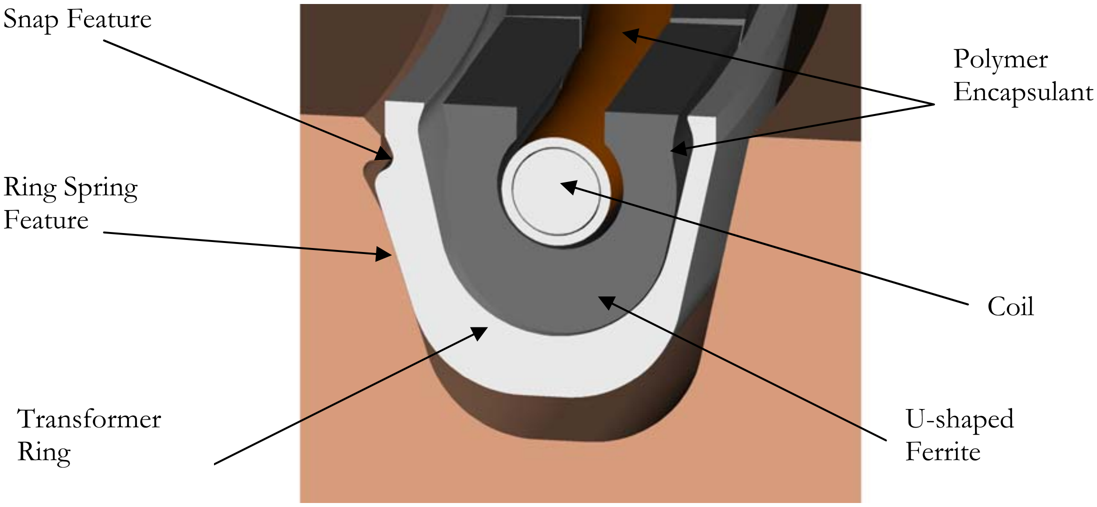


Figure 10. *Half-transformer cross section (shown partially compressed.)*

Accordingly, the ferrite may be provided as small, strong segments, as shown. The ferrite segments (and transformer wire) are encapsulated with an FEP polymer in a steel ring that provides mechanical protection and shape integrity to the coil and facilitates assembly of the coil into the protected groove in the tool joint.

In order to completely contain the magnetic field, the two U-shaped ferrite troughs must come together with as little gap between them as possible. If any part of the oscillating magnetic field leaks out of the transformer, it will induce eddy currents in the surrounding electrically-conducting steel, which will rob energy from the system. If even a small fraction of energy is lost in each joint, the cumulative energy loss through many joints could be prohibitive.

In IntelliPipe each half transformer is snapped into a groove in the face of the pipe's tool joint. As mentioned above, a double-shouldered tool joint design is ideal for precisely locating and protecting the two half-transformers. Excellent closure of two mating half-transformers is further ensured by spring loading each half-transformer ring against its mate. A spring force of several hundred pounds is achieved in the IntelliCoil design by creating a conical interface between the inner surface of the ring and the inner surface of its mounting groove. This feature is also known as a ring spring. Before adjacent joints of IntelliPipe are made up, the IntelliCoils protrude slightly above the secondary shoulders of the pin and box. As makeup proceeds, the mating rings engage each other, and each is pushed back into its groove. The net spring force arises from slight diametrical extension of each ring as it engages the conical inside surface of the groove.

The coil wire shown in the figure is a nickel-gold plated copper clad steel wire. The steel core facilitates strength and mechanical stability of the coil. At high frequencies, the skin effect confines the current in a conductor to its outer surface; hence the highly conductive outer plating of the wire. All portions of the coil which experience a potential that is alternately above or below ground potential must be perfectly electrically insulated from the drilling mud and the steel of the pipe, because any leakage of the signal to the adjacent grounded groove robs signal strength. To prevent any such signal loss, the wire is bonded to a polymer insulator, comprising PFA (Teflon®) or polyether ether ketone (PEEK®). The gold plating ensures longevity of electrical contact surfaces and also aids in bonding of the insulating coating to the wire. In the figure, the polymer encapsulant is shown as if it were transparent.

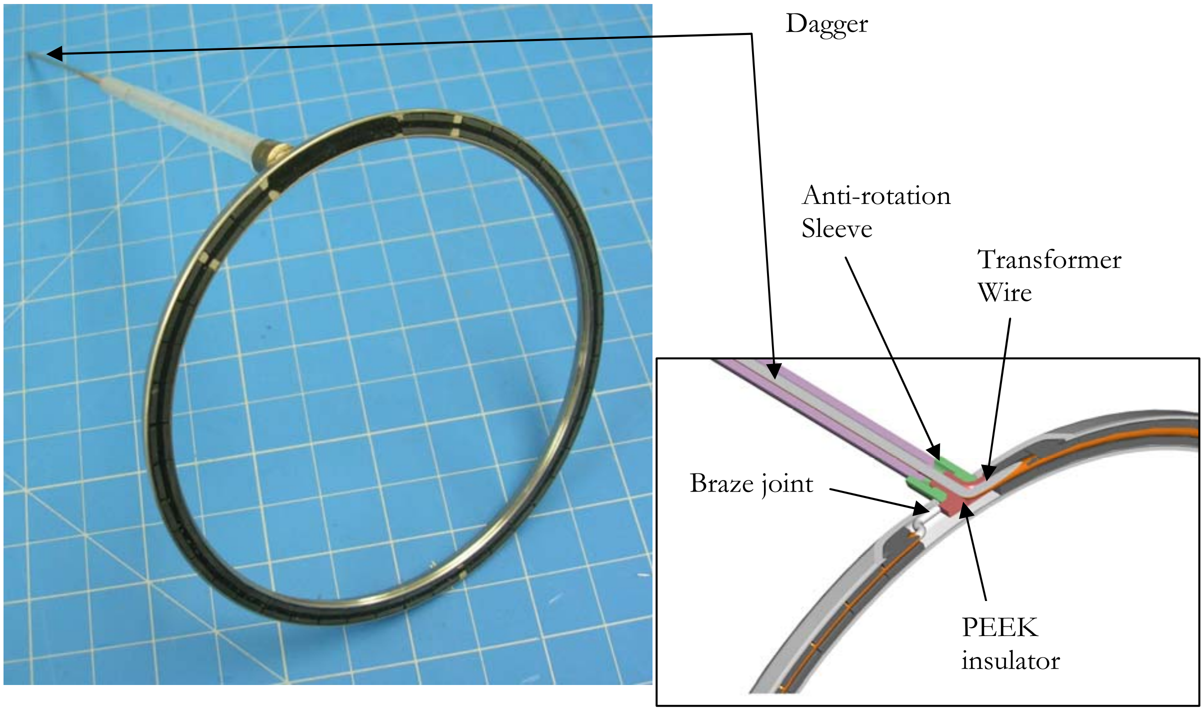


Figure 11. *IntelliCoil*™

Figure 11 shows the overall IntelliCoil assembly. The inductive coil is a simple single-turn transformer. At one end of the coil, the wire is brazed to the transformer ring to establish a permanent electrical ground connection. The ground circuit passes through the ring to the pipe, and finally to the cable shield in the data cable. At the other end of the coil the wire is bent at a 90-degree angle and passes through a small hole in the transformer ring to become a male connector ("dagger"). The dagger, with its gold plating, connects to the center conductor of the IntelliCoax. Thus the two mating half-transformers and the cable form a closed electrical loop. Notable features of the IntelliCoil design include a PEEK® insulator bridge that supports the bent wire against pressure loading, and an anti-rotation sleeve that prevents rotation and damage of the ring during makeup of the tool joint.

Assembly of IntelliCoils into IntelliCoax. The IntelliCoil ring is electrically connected through the dagger to the IntelliCoax via a special connector. Details of this connector are provided in **Figure 12**. The primary components responsible for proper electrical connection are the gold-plated dagger and the gold-plated dagger connector. The other parts of the connector facilitate precise blind assembly of the connection and ensure proper electrical insulation of the conductors. The dagger connector incorporates two spring-loaded contacts that accommodate the two different wire gages of the coaxial cable and the transformer ring dagger. These spring contacts are effective in providing electrical contact under vibratory loading. The housing of the dagger

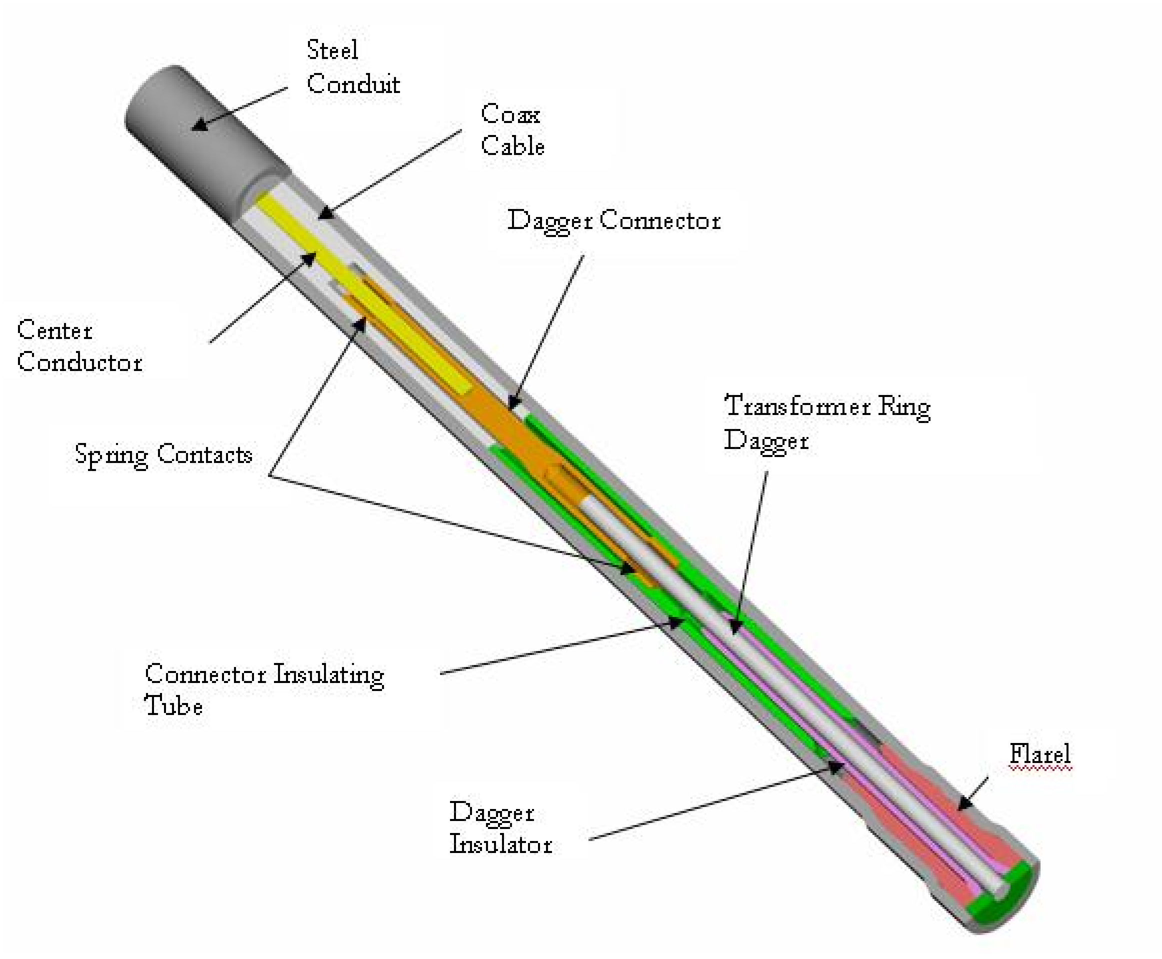


Figure 12. *Cross sectional view of the IntelliCoil-IntelliCoax connection*

connector is constructed of a brass alloy and is nickel plated for corrosion resistance. The two springs inserted into each end are made of a beryllium copper alloy for high temperature operation and are further plated with nickel and gold for superior electrical contact and corrosion resistance. An elastomeric seal stack ensures that all connections remain dry, even under severe downhole conditions.

Details of this seal stack are shown in **Figure 13**. Several components – a ceramic backup, a two-piece Teflon® backup, and a redundant stack of o-ring seals and backups – are required to provide a reliable sealed environment. A fluorocarbon gel is used to lubricate the seal stack. It also helps to prevent cracking of the elastomeric seal materials under long-term exposure to high pressure and temperature and provides a barrier to water that might be deposited by condensation on the connecting surfaces.

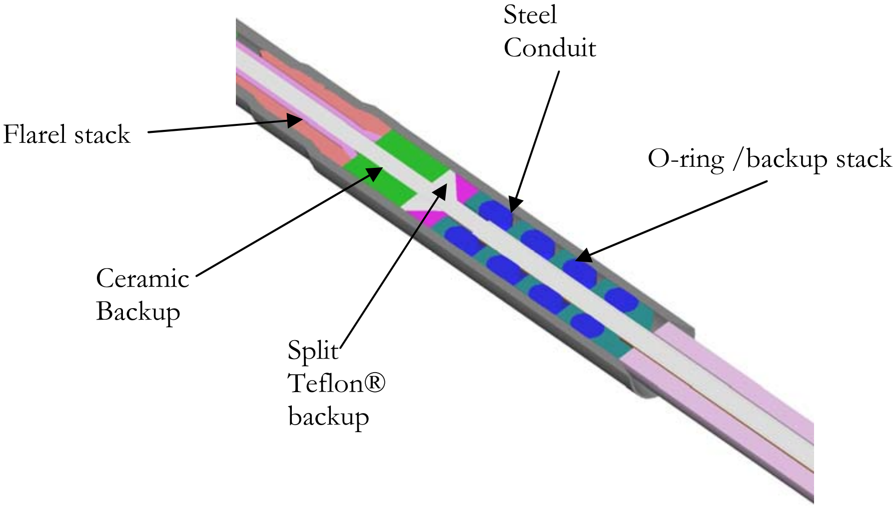


Figure 13. *Seal stack inside IntelliCoax™*

IntelliDrillCollars™, IntelliHeavyweight™, IntelliStabilizers™. It is a reasonably straightforward procedure to incorporate the same IntelliCoil couplers, IntelliCoax, grooves, gun-drilled holes, cable anchors, and seal systems that are used in IntelliPipe into other intelligent tubulars, such as heavyweight drill pipe, drill collars, and stabilizers. However, there is one design "wrinkle" to downhole components that have a uniform inner diameter from end to end. Having no internal upset, they provide a different challenge for insertion of the IntelliCoax. Gun drilling technology will not allow accurate placement of a single small bore inside the collar wall over the thirty foot length of the pipe, so the data cable cannot run straight from end to end as in the previously described IntelliPipe design. The cable must make the transition from inside the wall of the pipe (which coincides with the IntelliCoil ring diameter) out into the bore of the tubular, to run along its inside wall, as shown in **Figure 14**. This transition is accomplished by milling a slot in the ID of the tubular to provide a gradual transition between the pipe bore and the gun drilled hole (see inset). This design retains the placement of the IntelliCoil dagger and the IntelliCoax cable within the protecting wall of the tool joint. It also enables assembly of the ring and cable using the same technology that is used for internally-upset tubulars.

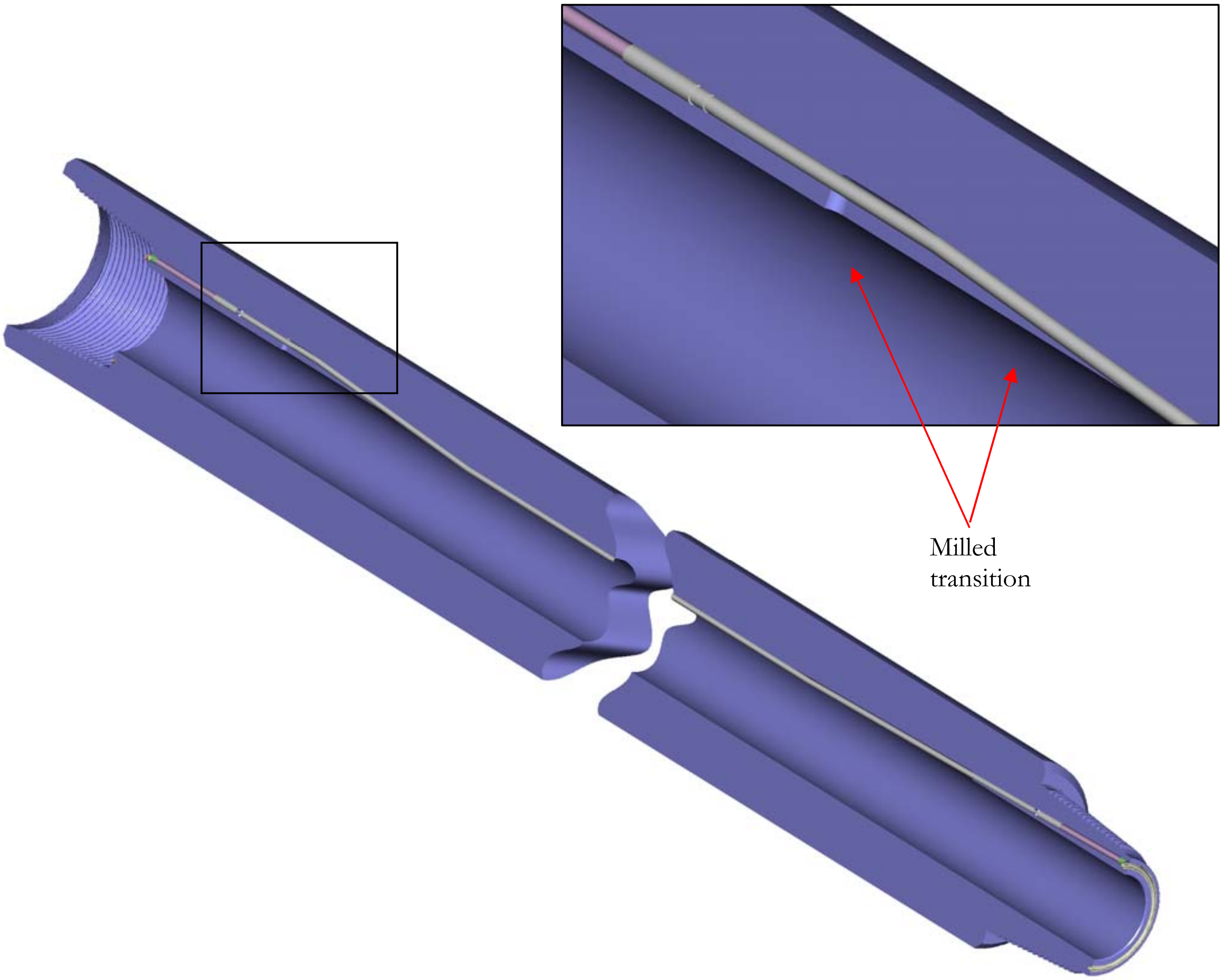


Figure 14. *Data cable routing for drill collars, heavyweight, and stabilizers*

IntelliMotors™ and IntelliJars®. Wiring of drilling jars and motors presents additional design challenges because these devices create relative linear and rotary motion, respectively. In the case of a motor, the rotary motion can be accommodated by a rotary IntelliCoil coupler, similar in function to the data swivel coupler discussed above. The eccentric motion (nutation) of a Moineau motor shaft can be accommodated by flexure of an armored coaxial cable, such as is used by the wired tubulars. The specific details of wiring a motor (through internal connections, coupling assemblies, etc.) are peculiar to each of the various motor designs and are worked out with each manufacturer under confidentiality agreements.

In a jar, the primary design challenge is to create an extensible transmission line and to locate it within a protected region in the tool. The simplest and most robust option for achieving extensibility is to wind a portion of the armored coaxial cable into a coil spring. This approach does not require sliding connections and seals and maintains the integrity of the armored stainless steel cable through the full length of the tool. Again, the armored coax cable design facilitates this requirement. A cable clamp allows tensioning of the straight portion of the cable that continues beyond the extensible section. In addition to features to retain the armored cable, the jar must usually be provided with end subs ("crossover subs") to provide the proper double shouldered thread. All other jar parts are unmodified. Specific embodiments of these design concepts are peculiar to each of the jar designs and are worked out with each manufacturer under confidentiality agreements.

Misc Drill String Components – IntelliSubs™. Rented BHA components such as kellys, reamers, stabilizers, non-magnetic drill collars, etc. may be wired without making permanent modifications to those tools. This is enabled by providing an intelligent crossover sub at each end of the rental component and by stretching and anchoring the armored cable between the intelligent crossovers. **Figure 15** illustrates this approach with a stabilizer. This method has been applied with success to a 5-1/4" hex kelly and to 8-1/2" roller reamers.

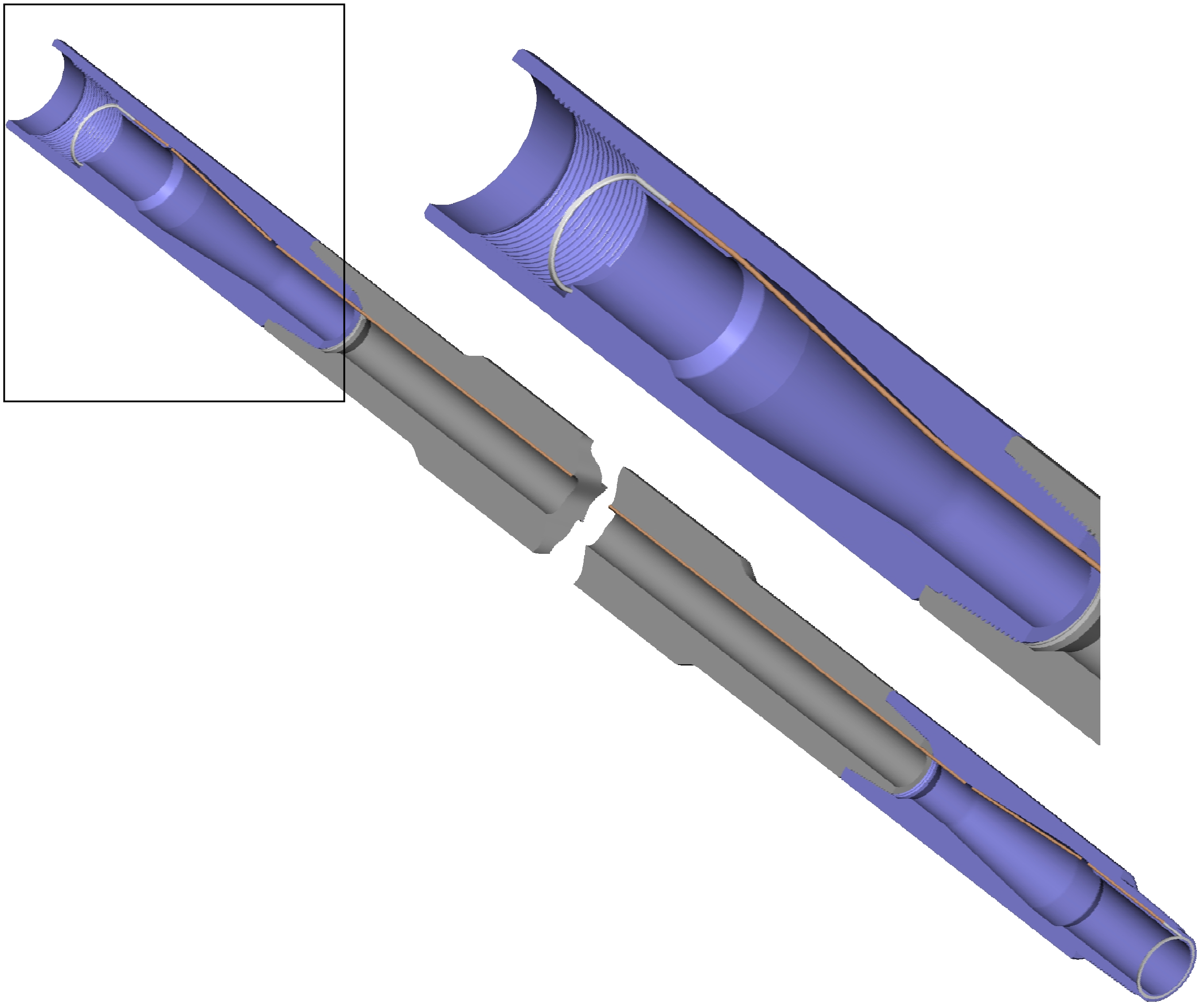


Figure 15. *Wired rental stabilizer, terminated at each end with IntelliSubs*

IntelliValves™ and Other Split-body Designs. Some drillstring components require an obstruction to be placed in the middle of the pipe that prevents passage of the IntelliCoax through the center of the device. Examples of this include a kelly valve and a mud screen. In such tools, the coaxial cable is routed around the obstruction, as shown in **Figure 16**. Here a split housing is employed that sandwiches the obstruction (valve) between two threaded subassemblies. Insulated wires are routed inside the walls of each of the subassemblies. Also notable in this example is that the primary shoulder of the connection, rather than the secondary shoulder, is used to house the IntelliCoil. This particular feature may vary according to the constraints of the particular device being wired.

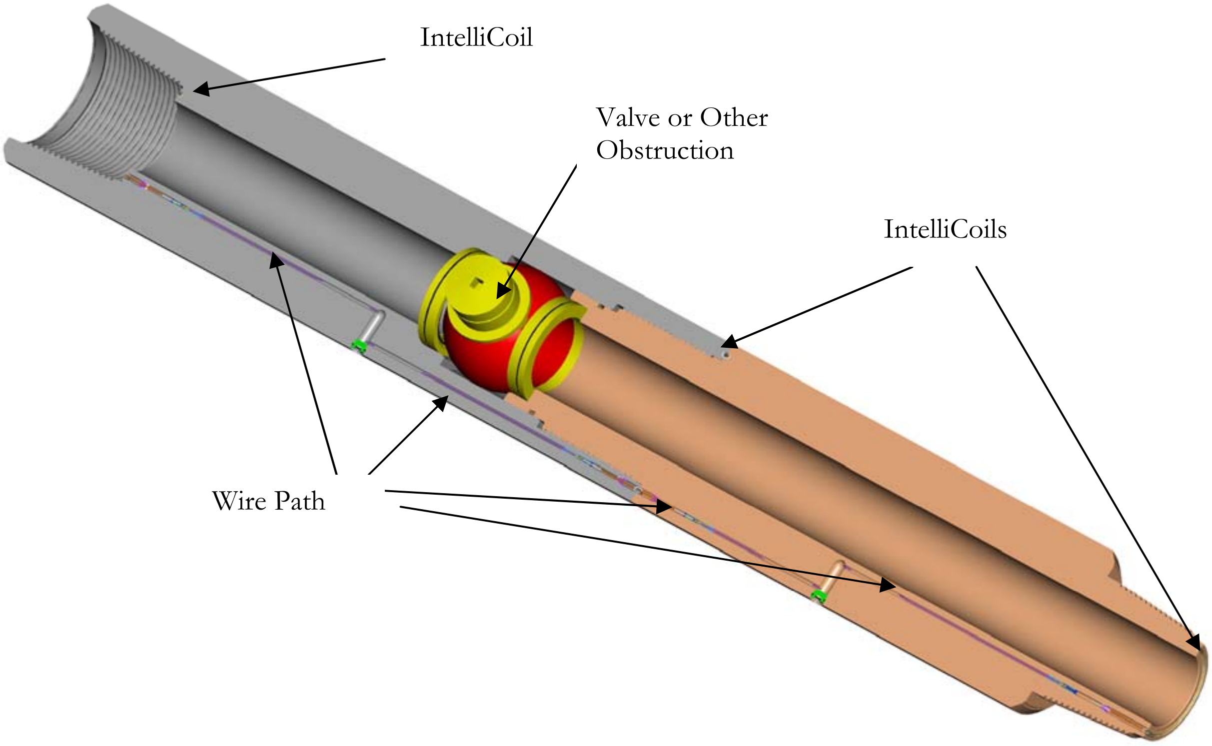


Figure 16. *Wiring of components with thru-bore obstructions*

EXPERIMENTAL

The research and development work completed during the course of the project may be classified into three major divisions: mechanical, electronic, and software development. The mechanical division of effort was concerned with the development of the IntelliServ transmission line. This facet of the project included design of extreme environment wiring components; routing of cabling through various downhole tools; and designing protective enclosures for Link electronics, sensors, and other application-interfacing components. The electronic-related efforts focused on developing the networking hardware and firmware required to move data over the transmission line at high speed. Primary tasks in this area included providing temperature-robust Link electronics (ultimately to include custom high-temperature integrated circuits), assisting in development of other electronic interfacing components, and design of diagnostic equipment to ascertain the health of the transmission line and IntelliLinks. Software development was the outermost "layer" of the networking product and focused on providing the necessary programming support to the network, including user interfaces, applications (data logging, vital statistics, etc), and networking functions.

Basic design goals

In each of the efforts mentioned above, the primary goal has been to provide a high-speed communications network that:

1. reliably delivers data and tool control signals under various drilling conditions, including high temperature, high pressure (HTHP) wells up to 200C and 25ksi
2. is universally useful for the suite of existing logging and measurement tools, as well as for new tools designed specifically to take advantage of the IntelliServ network capabilities
3. has a customer-usable bandwidth of 1 million bits/sec
4. has a minimum passive transmission range (Link-to-Link) of 1000 ft under the most severe borehole conditions
5. can service wells of practically any depth

Experimental procedures have been utilized that have lead stepwise to verification of each of these goals.

Mechanical R&D - development of robust drill pipe transmission line

Development of the mechanical portion of the IntelliServ system (the transmission line) has focused on design and validation of two major interdependent subsystems: the armored data cable and the data couplers at each end of the cable. Proper electrical characterization and analysis of the various designs and the interactions between subsystems required the development of mathematical and physical models. Successful designs were then implemented into full diameter prototypes and subsequently into full length prototypes for in-well validation.

Electrical modeling of transmission line components – mathematical and physical. The IntelliServ transmission line can be modeled as an assembly of resistors, capacitors and inductors. These interact to give pass bands or transmission peaks and group delay minima or "bathtubs." The IntelliServ network functions most efficiently under conditions where attenuation is low, the pass band is wide, and the variation of group delay with frequency (dispersion or distortion) is low.

In principle it should be possible to accurately measure a single IntelliCoil coupler and a single length of cable (together with its connection to the coupler) and to mathematically model a complete multi-pipe system from those measurements. In practice, however, it has proven more practical and more accurate to measure several physical components together. For this reason, bench-top models have been built that duplicate, as exactly as possible, all elements that are present in the pipe and the joints. One end of an early physical model, which includes 30 simulated joints of pipe, is shown in **Figure 17**. In this model, steel rings containing prototype IntelliCoils were mated and taped together to fix the position of the coils. The steel rings simulate the steel immediately surrounding the IntelliCoils in a pipe tool joint. Coaxial cables approximately 32 ft long were strung between the ring pairs to complete the simulation of the electrical qualities of a wired drill pipe. Up to 30 such assemblies were connected in series to create approximately 1000 ft of transmission line.

This model enabled measurement of the frequency response of the simulated systems with a spectrum analyzer (shown second from left). Various coil and cable configurations were tested in this configuration. All testing with this model was done at room temperature. Note the loudspeakers: the first test of the system was transmission of high-fidelity music from computer's CD player, facilitated by frequency modulation of a 5 MHz carrier signal. The FM modem is located under the speakers.

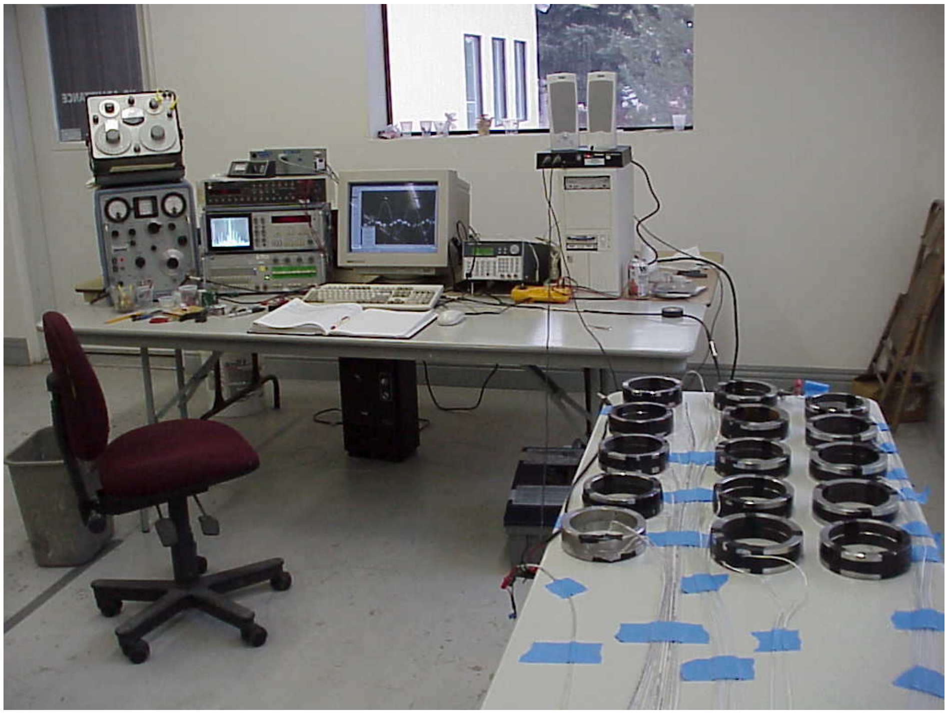
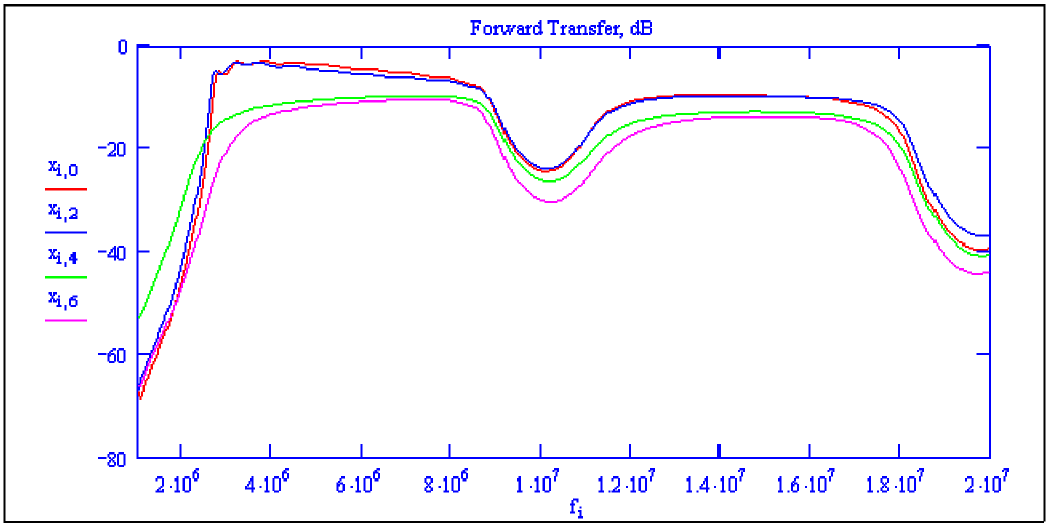
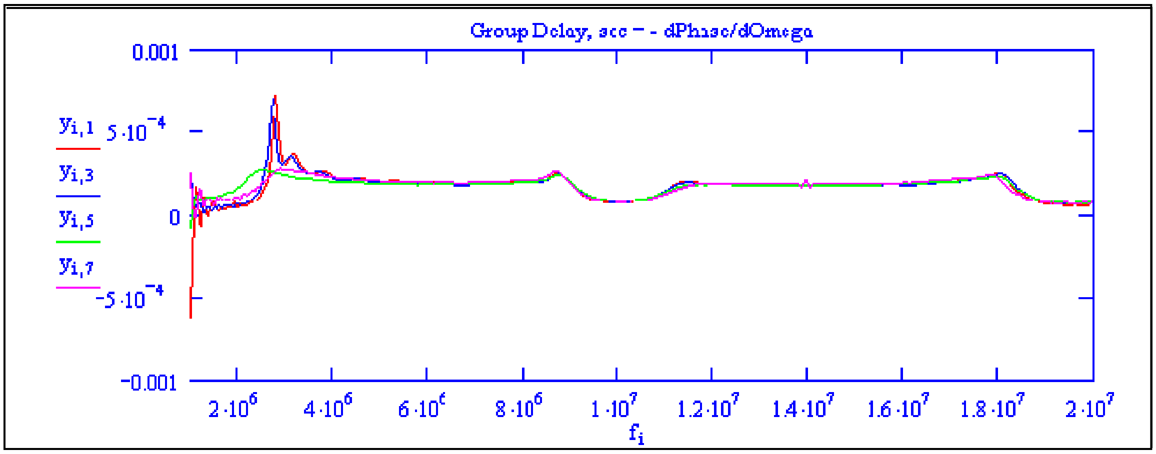


Figure 17. *Bench-top Laboratory Testing of 30 "Joints"*

In tandem with this work, a mathematical model was built and calibrated using data from the physical model. This model was built on a MathCAD platform that uses chain matrices to predict the electrical characteristics of a drill string comprised of an arbitrary number of drill pipes. The mathematical model was built to help predict the effects of changes to system variables, thereby speeding the optimization process. Variables of interest to the design process include the number of turns in the inductive couplers, the parameters of the data cable, and the geometry of the ferrite that surrounds the couplers. **Figure 18** shows representative output of the model, plotting both attenuation and group delay vs. frequency for a string of 9 pipes with four different types of cable.



(a)



(b)

Figure 18. *Attenuation (a) and Group delay (b) for System of 9 Simulated Pipes*

A more compact and portable physical model was later developed that allowed simulation of approximately a mile of IntelliPipe. Wired drill pipes were simulated using discrete and distributed capacitance, inductance, and resistance elements that closely matched measured values from actual components used in drill pipe. This pipe simulator is shown in **Figure 19**. The coaxial cable portion of the transmission line is simulated by nominal 32-foot lengths of bare coaxial cable that vary randomly in length to simulate the normal variation in drill pipe. These are wrapped around a spool, with each cable segment terminated by discrete inductances mounted on the spool flange. This construction provides a very flexible tool that allows for configuration or measurement of the system at any joint in the simulated string. Its size also makes it possible to ship the physical model to offsite collaborators. This model has been proved especially useful in verifying the operation of network hardware.

Figure 19. *Compact physical model - simulation of 1 mile of drill pipe*

As the design of the transmission line elements matured and stabilized, a very accurate physical model was developed that incorporates a full physical representation of all transmission line components, including nominal 32-ft. lengths of armored coaxial cable (with slight random variation in length), full size IntelliCoil rings, and the actual connection scheme used in the drill pipe. This compact transmission line is shown in **Figure 20**. The armored coaxial cable has been coiled to make the assembly more compact -- coiling at this diameter has negligible effect on cable behavior. IntelliCoil rings are embedded in steel plates that duplicate the near-field effects of the steel in tool joints. This compact model duplicates a 1,900-foot drill string.

Figure 20. *Physical model used in temperature testing*

This compact transmission line has been used for quantifying the effects of temperature on the electrical properties of the wired drill string. The whole model, including 60 simulated joints of drill pipe, was placed in a large electrical furnace (shown in the figure) and heated to temperatures as high as 200C. Quantitative data regarding the attenuation and group delay characteristics of the system were gathered using a network analyzer. Digital data was also transmitted through the simulated drill string and data quality was quantified as bit error rate. Because the model accurately reproduces the electrical characteristics of the actual drill pipe, it has also been used to qualify new designs and new production lots of IntelliCoils.

Mechanical Modeling – Finite Element Analysis (FEA) and fatigue testing. As shown previously, wiring a drill pipe requires certain modifications to be made to the pipe. These modifications have been analyzed both by predictive FEA and by laboratory testing. This included: 1) axisymmetric FEA modeling of a standard double shouldered tool joint connection (for a base line); 2) axisymmetric FEA modeling of the IntelliPipe® modified double shouldered tool joint connection; 3) 3D FEA modeling of the modified internal upset geometry and connection; and 4) full scale drill pipe fatigue testing. FEA modeling was done at Novatek and Grant Prideco facilities, using Cosmos™ and Abaqus™ analysis packages respectively. Full scale fatigue testing was done using cantilever beam fatigue machines located at Grant Prideco's Houston facility. The test pipe included all IntelliPipe® modifications. Ten test samples including box and pin ends of the drill pipe were tested to failure. To expedite the fatigue testing, large bending moments equivalent to dogleg severity of 32 degrees per 100 ft were employed, and high rotational speeds were used to accelerate fatigue. Visual examinations and further detailed analyses by the Grant Prideco Metallurgical Department were used to assess failure origins. This testing has assured that the wired tubulars meet all the mechanical specifications of the original tubulars that have already been proven in the field.

Component Testing – HTHP conditions. To ensure fitness of transmission line components in a high pressure/high temperature environment, many tests of individual components were conducted in a small pressure chamber. This chamber, shown in **Figure 21**, can generate an environment of 25,000 psi and 200 degrees C.

The primary focus of the high pressure/high temperature testing has been the sealed connection between the IntelliCoil dagger and the data cable (see Figure 13.) Several different simplified configurations of this connection, shown in **Figure 22**, have been tested in the pressure chamber. The various configurations mimic the cable and dagger geometries and loading conditions expected in service. In these assemblies, a powdered dye or indicator paper was inserted in the sealed tube to serve as a moisture indicator.

The test assemblies were placed in the pressure chamber, which was filled with tap water. The temperature was then increased to 200 C, 150 C, or 85 C, or left at room temperature, and the pressure was adjusted to maximum design pressure (25,000 psi). This set of conditions was maintained for a period of a few hours to a few weeks. During the initial period of pressurization, the pressure gage was watched closely for any sudden drop in pressure. If this occurred, the test was aborted and the sample was inspected for the cause of failure. Upon completion of the test, cool fluid was pumped around the pressure chamber, and the chamber was brought to room temperature prior to releasing any residual pressure, allowing for condensation of any fluids that may have compromised the seals. The test samples were then inspected for any sign of seal or structural failure.

Figure 21. *Small high temperature/high pressure test chamber*

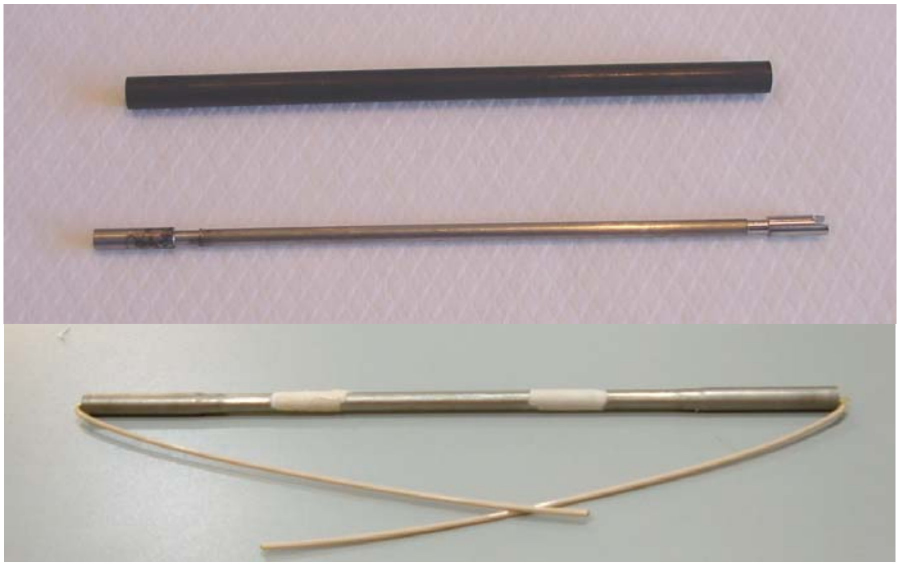


Figure 22. *Samples tested at high pressure and high temperature*

Testing of larger components and subassemblies (e.g., full IntelliCoil rings and Link electronics assemblies) has been accomplished using similar procedures in a larger pressure vessel, shown in **Figure 23**.

Figure 23. *Large HTHP test vessel*

Tensile testing of conduit and conduit retention features. Tensile tests on the conduit were performed using an apparatus comprising a hydraulic load cylinder, a force gage, and an I-beam frame as shown in **Figure 24**. Each data cable anchor design (see Figure 8) was tested by assembling the retention mechanism, together with a 6-inch length of data cable tubing, into the apparatus. The free end of the data cable tubing was clamped in the apparatus, and the sample retainer was placed in a slotted holder (just to the right of the force gage in Figure 24). The assembly was then pulled to failure and the load and location of the break was recorded. Testing of short samples was followed by testing full length (32 ft.) cable samples in the same fixtures. The full-length samples were pulled to tensile failure and load-deflection data was also taken for each sample to obtain stress/strain characteristics of the full cable. Both of these tests were conducted to ensure that the cable and anchor were capable of withstanding strains expected during field deployment of wired drill pipe.

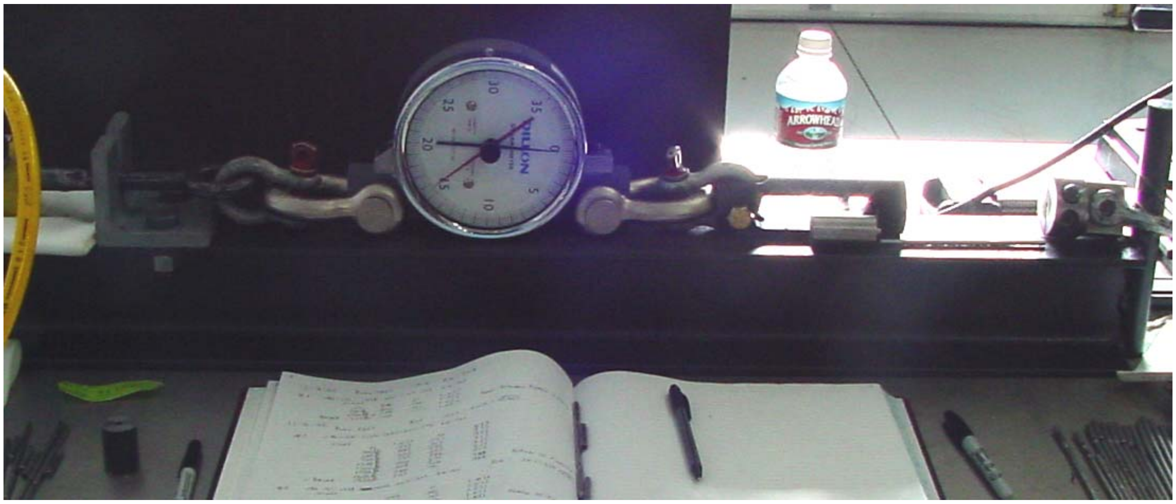


Figure 24. *Tensile test apparatus*

Torsion tests of IntelliPipe joints and IntelliCoil retention features. Torsion tests were performed to ensure adequate performance of the IntelliCoil rings under the high torsional loads applied to the tool joint during joint makeup. As many as 150 make and break cycles were applied to a single joint. Best-O-Life Premium Blend copper thread dope was applied to the tool joint per manufacturer's recommendation. The joint was made up by hand and was then tightened with a Scorpion® brand make-up unit to the recommended maximum torque of 56.6 kft-lbf . The joint was then broken out to the hand tight condition and taken to full torque without inspection or further application of grease. After five such make/break cycles to full torque the joint was then fully broken out, visually inspected, regreased, and again taken five times to full torque. This process was repeated until the prescribed number of cycles was accomplished. The tool joints were then cleaned and inspected for damage or for any rotation of the data coupler rings.

Abusive field handling procedures were also simulated, such as rotating the secondary shoulder of the pin connection under load against the primary shoulder of the box connection and dropping the secondary pin shoulder onto the primary box shoulder.

Assembly testing – drill pipe. Validation of full wired drill pipe assemblies has been accomplished on several levels. First, newly-completed individual drill pipe assemblies were evaluated on the benchtop for appropriate electrical characteristics using a network analyzer. Special test tools containing IntelliCoil rings that mate with those in the drill pipe were developed to enable communication with a single pipe. These tools were in turn connected to a network analyzer, thereby allowing the characteristic frequency response (forward transfer) of the pipe to be recorded. This setup is shown in **Figure 25**. This test is used in production and enables assemblies with substandard electrical characteristics (low magnitude or bandwidth) to be identified and repaired.

Following successful bench testing, wired component assemblies were validated in a shallow well at the Novatek site, first under high internal pressure and subsequently under rotation. The high internal pressure (up to 12,500 psi, depending on the tubular) was useful in determining competence of seals and IntelliCoil assemblies. During the pressure tests, forward transfer measurements were used to monitor line characteristics for up to several hours. Deviations in transmission characteristics over the course of the test would indicate substandard assemblies. Vibrations generated during rotation of the assembly in a well were useful primarily in identifying substandard electrical connections. Standard bit error rate testing (BERT) was used to provide a quantitative detection of transient changes in line quality that may occur too rapidly for detection by forward transfer analysis.

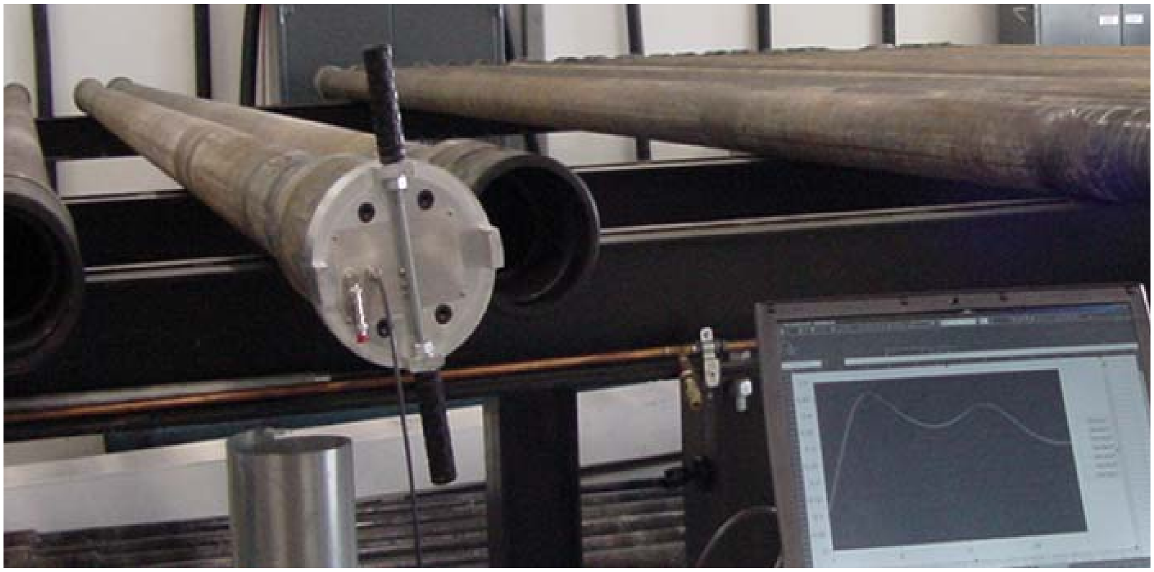


Figure 25. *Wired pipe test tools*

Field string diagnostics, including Time Domain Reflectometry. Test tools similar to those shown in Figure 25 were used for diagnostic testing of non-conforming strings of pipe using time-domain reflectometry (TDR.)[2] With TDR[iii,iv] the location of a cable fault or faulty IntelliCoil inside a single wired tubular can be pinpointed. This technology was also applied for determining where a transmission line fault occurred within a string of several drill pipes. For example, if communication with the uppermost Link failed, TDR was applied to determine whether or not the fault was in the Link or in an intervening pipe. The location of the failed pipe could also be

Figure 26. *Test equipment used for field debugging, including* TDR

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[2] TDR tests are well known to the networking industry for similar network fault debugging activities

determined, so that the stand containing that pipe could be removed during the next trip out of hole. Both the forward transfer test and the reflection test require the use of a network analyzer and a dedicated laptop computer. Such equipment is not well suited to the abuse expected during field deployment of the wired pipe. These tests required substantial setup and interpretation, and non-productive down time (NPT) during drilling must be minimized. For this reason, fit-for-purpose test equipment was developed for the field. This equipment, shown in **Figure 26**, embodies the basic features provided by the bench equipment and enables simplified pass/fail testing in the field, including forward transfer and TDR.

Testing of drilling jars. Weatherford International provided the first jar for wiring. In cooperation with Weatherford engineers, this 6½" hydraulic jar was made IntelliServ-ready by modifying it to accommodate the special extensible cable (described above) and to accept standard IntelliCoil couplers at the threaded connections at each end. A first prototype jar was assembled and validated using the methods described above. The prototype was then qualified by slowly stroking it from the fully closed position to the fully open position at least 60 times. The jar was then fired a total of 110 times. Both tests were conducted in a Weatherford facility, using standard jar test equipment. **Figure 27** shows the setup used in the jar firing test, complete with simulated drill string mass and compliance. The jar is on the far end of the assembly. This test is considered to be an extreme test of the robustness of the IntelliServ components – indeed, it is quite uncommon for a jar to fire 110 times during a single deployment. Once a jar has been deployed in a pre-determined number of wells (usually one or two), it is usually completely rebuilt. Upon successful completion of these initial qualification tests, one more prototype jar was built to the same design for deployment to the field.

Figure 27. *Jar Test Setup*

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Field application testing – compatibility with darts, wiper balls, and wireline tools. When a wired tubular component is bent, as in deviated drilling, the coaxial cable inside the pipe can move towards the center of the pipe and intrude into the flow space. Concern has been expressed that this intrusion might hinder wireline or cleaning tools that must pass through the center of the pipe.

Initial laboratory testing with Weatherford wiper darts was undertaken in February of 2004 and indicated that the IntelliCoax configuration, in both both 5" and 5-7/8" pipes, does not damage the darts or alter their wiping efficiency, even when the pipes are bent to a dogleg severity (DLS) of 7.5°. To d gain further confidence with a longer drillstring and a wider sampling of in-pipe operations, approximately 40 joints of 5-7/8" IntelliPipe® were shipped to the GTI-Catoosa facility in Oklahoma in September of 2004.

In this test, a string of thirty-one 5-7/8" IntelliPipe joints and one IntelliLink was run into a wellbore that provided a maximum DLS of 9.56°/100 ft. Tests were then conducted while orienting the string rotationally in 4 x 90 degree increments to allow the IntelliCoax within the pipe to experience worst-case exposure to any tools or devices run into the bore. The following items were then run through the 32 pipes:

1. Gyro survey tool with 3 centralizers (**Figure 28**), first at a deployment speed of 54-55 fpm deployment speed, then at up to 200 fpm.

Figure 28. *Gyro Survey Tool*

2. Gyro assembly with muleshoe tip (more aggressive nose profile – see **Figure 29**) at up to 200 fpm.

Figure 29. *Muleshoe Tip*

3. Free point indicator tool (with 2 centralizers – see **Figure 30**), with and without a string shot, at 200 fpm.

Figure 30. *Free Point Indicator Tool*

4. A string shot without a free point indicator tool and without centralizers, at between 300 and 390 fpm.
5. A wet-connect tool (**Figure 31**) was gravity deployed to 300 ft above its male connector, then was pumped the remainder of the way

Figure 31. *Wet-Connect Tool*

6. Four 8.66” Halliburton foam wiper balls (**Figure 32**) at a flow rate of 320 gpm.

Figure 32. *Foam and Hard Rubber Wiper Balls*

7. Four 5.5” Halliburton hard rubber wiper balls (also Figure 32) at approximately 320 gpm over the majority of the drill string, with lower flow rate when the balls passed through smaller diameter sections.

Conclusions from field application testing of darts, wiper balls, and wireline operations on IntelliServ tubulars, September 2004.

No tension or speed anomalies were noted during any of the runs for the centralized gyro survey tool, the gyro assembly with the muleshoe, the uncentralized string shot (without free point indicator), and the wet connect tool.

a. At final depth, the free point indicator tool was able to fix to the inner wall of the drill pipe without difficulty and calibrate.
b. At final depth the wet connect tool latched correctly.
c. All foam balls were retrieved without damage, in a condition where they could be used again.
d. All hard rubber balls were retrieved with minimal damage. Some minor scratches appeared to be due to engagement with the IntelliCoax™ (see **Figure 33**). All balls were judged to be reusable.

Figure 33. *Damage to Hard Rubber Wiper Ball*

In all cases, the IntelliServ network was monitored continuously and performed without error. This test verifies that cable is compatible with a variety of in-pipe operations in wellbore deviations up to almost 10°/100 ft.

For each of the tested devices, proper functioning of the device was evaluated (e.g., latching of the free point indicator tool and the wet connect). Proper motion of the tools was verified by monitoring deployment speed and, in the case of the wiper balls, deployment pressure. Function of the IntelliServ network was verified for the duration of the test by sending continuous data and recording any transmission errors. Drill string forward transfer measurements were also taken by programming a Link to transmit a 1-8 MHz frequency sweep on demand. The transmitted signal was recorded on a storage oscilloscope at the surface.

Electronic & Software R&D – development of networking electronics

Development of the electronic portion of the network has focused on building Link modules that are capable of a) transmitting data at rates in the Mbit/second range and b) operating under downhole conditions including high temperatures and high levels of shock and vibration. As described above, Links function both to control internal networking functions and to provide an interface with other intelligent down-hole tools.

Roadmap – prototype to commercial product. To accomplish both these objectives, electronic package capabilities were systematically improved from low-speed, low-temperature prototypes to the intermediate-speed, intermediate-temperature link that is now deployed in the field and will see early commercial use. The final commercial product will function at high-speed and high temperature.. The biggest challenge in this effort was the limited availability of commercial electronic components that are rated for downhole conditions. As a result of this limitation, much of the development effort included qualification of electronic components at temperatures above standard industrial ratings, and then building desired functionality into a highly limited set of components. To alleviate these concerns for the long term and to provide for improved system reliability, some of the development effort was focused on development of high-temperature application specific integrated circuits (ASICs) using silicon-on-insulator (SOI) technology.

The first electronic prototypes utilized simple analog transceivers to provide frequency modulation and demodulation of analog vibration data (Beethoven's Symphony No. V) onto a 5 MHz carrier frequency. The modem had been previously developed for use with the ultrasonic acoustic coupler shown in Figure 1. This prototype provided a dramatic early demonstration of the functionality of the unique IntelliServ transmission line and led to early participation of industry partners.

A second, more sophisticated system was then developed to enable transmission of digital data and to provide for more quantitative analysis of the transmission line. This prototype, known as the "Catoosa" system, utilized commercial grade electronic components that were limited to 85C. Modem firmware was implemented in a field-programmable gate array (FPGA). This design contained a 2 Mbit/s backbone and other functionality that made it ideal for proving out the transmission line as it was being developed. However, its ability to interface with external tools was quite limited. This limitation, along with its temperature limitation, has restricted its practical application to research activities. Though it is not presently used for field applications, it is still used in IntelliPipe qualification testing at the Provo facility.

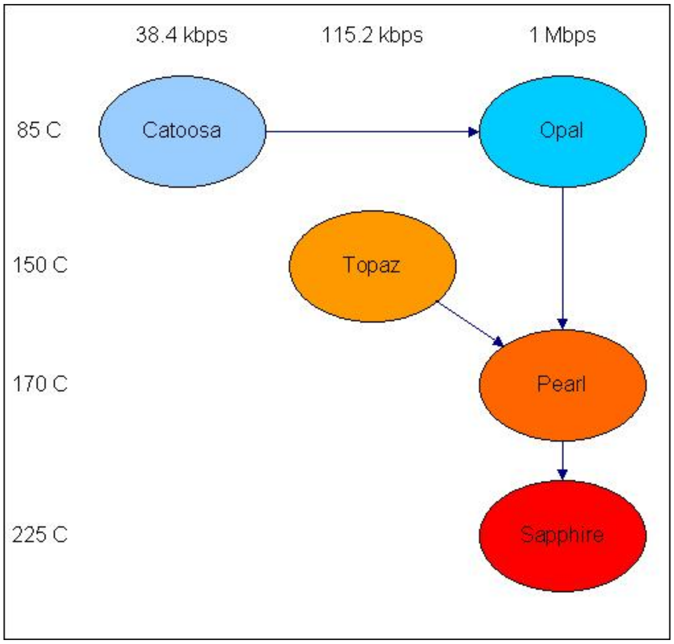


Figure 34. *Roadmap to High Data Bandwidth and High Operating Temperature*

Figure 34 shows the roadmap for electronic system development. The early Catoosa system has been followed by two intermediate prototypes: 1) the Opal system is a test iteration that still utilizes temperature-limited commercial grade products, but it expands upon and improves the capabilities of the Catoosa 2 Mbit/s backbone, adding high-speed interfacing with external tools, in preparation for higher temperature implementation of the system; 2) the Topaz system provides for medium temperature service (150C), while utilizing a slower backbone – this system allows for robust field service while other more sophisticated systems are being developed. Topaz IntelliLinks were first deployed in a field test well in October 2004 and are expected to provide for initial commercial use of the network.

Both of these intermediate prototypes are precursors to the Pearl system, which combines the high speed backbone of Opal with medium-high temperature service exceeding that of Topaz. Pearl IntelliLinks are currently under development. An initial prototype is currently operating on the bench and is successfully demonstrating network operation.

Electronic and network development will culminate in the Sapphire system. Sapphire IntelliLinks incorporate the same functionality achieved with Pearl into a high temperature package based around SOI ASIC components. Note that the indicated data rates are the full net data rate available to the customer. The network backbone, with network overhead and reserve for future Link functionality, functions at up to twice this data rate.

Testing procedures – Topaz. Due to the temperature requirements of deep-hole drilling, all circuitry must be tested and proven compliant for extreme thermal load. Standard commercially available electronic components typically are qualified for operation between -20 degrees C and +85 degrees C. Industrial components (or military grade components) can be purchased which are qualified between -40 degrees C and +125 degrees C. The current design target is for electronic components that will operate between -40 degrees C and +200 degrees C, and eventually as hot as +225 to +250 degrees C.

Currently the oil and gas drilling industry standard is to qualify industrial components at temperatures of 170 degrees C. A very few devices have been qualified for short durations at 180 degrees C and even fewer have claimed operating tools at 200 degrees C. Operation of electronic components at these temperatures greatly reduces their lifetime. These elevated temperatures cause the integrated circuits to fail within 1000 to 2000 hours. Failure arises from mechanical strain due to differential thermal expansion of the different materials in the chip, from chemical and electrical breakdown of materials at high temperature, and from failure of the metal interconnects due to electro-migration of material under high current densities.

In order to adequately qualify electronic components, Novatek has developed high temperature testing capabilities. Testing electronic components at these extreme temperatures is pretty much a new art. Very few other companies are engaged in developing the skill. Of these, Sandia National Labs has been helpful in sharing its experience.

Initial testing of the Topaz system was quite rigorous in order to gain confidence for field deployment. The dynamic range of the system at temperature was quantified using the electrical mock-up of the drill pipe transmission line that was shown in Figure 19. Thermal loading conditions between -20C and 160C were created using a Delta Design Model 9039 environmental test chamber. This setup is shown in **Figure 35**. Up to 3 tested circuit boards are placed in an environmental test chamber, which is ramped up in temperature to 160C and held for an extended period of time. A sequence of ASCII characters is transmitted by the boards (while at temperature) through a simulated transmission line up to a mile long, and any character errors are tabulated. (The transmission line mock-up is not at temperature, as shown at lower right, below the oven.)

Figure 35. *Oven qualification of circuit boards through simulated transmission line*

Following this initial test, 25 Topaz printed circuit assemblies (PCAs) were assembled with SN96 solder (melting point = +221 C). Eight of these circuit boards were placed in the environmental test chamber.

Figure *36* shows the temperature test chamber and the configuration of the PCAs.

Figure 36. *Printed Circuit Boards operating inside the Test Chamber*

The following tests were accomplished with this setup:

1. The first board was held in the test chamber between +150C and +165C for a total of 42 days (approx. 1000 hrs). It was cycled to room temperature 15 times for times ranging from 30 minutes to 12 hours.
2. After the first board had already been in the chamber for several days, the second and third test boards were deployed in the chamber under the same conditions and were left in the chamber for 20 days (approx 480 hrs).

3. The fourth board had only the power supply loaded with a 50mA load. This board was inside the chamber for approximately 2000 hrs, with similar cycling to room temperature as experienced by the first 3 boards.
4. Three more PCAs logged 1250 hrs at +150C and continue to operate in the test chamber. These three have also been cycled to operate at -20C for some portion of their total operating hours.
5. The last PCA logged 270 hrs at +150C and continues to operate in the test chamber.

While in the test chamber the circuit boards were subjected to bit error rate testing (BERT). A typical BERT consists of transmitting random streams of bits through the communication channel (in this case the circuit boards). The resulting received data stream is compared to the original stream to determine if any bit errors have occurred. All errors are logged and statistics are computed. During BERT analysis, test bits were transmitted through varying lengths of simulated drill pipe as described above. Note that it is important to have the circuits operating during the test so as to duplicate local self-heating of rersistive components and to induce electro-migration in the metal traces in the integrated circuits.

Following initial testing successes, further efforts were directed at improving test capabilities and methods. For this purpose, two test facilities were built. One is provided with small volume ovens (see **Figure 37)** to facilitate individualized testing of components or small lots of components or assemblies. Typically these ovens are used for short term testing. The second facility has larger volume ovens (see **Figure 38.**) This facility is used for long term testing. The ovens are brought up to temperature and left for long periods -- 1000, 5000, and 10,000 hours. Testing in these facilities is ongoing.

Figure 37. *Small Volume Ovens (Delta Design)*

Figure 38. *Large Volume Ovens (Despatch)*

ASIC Developments – Sapphire. The ASIC design process is moving forward in planned increments.. Various modules of the overall electronics package are modeled and simulated using commercial integrated circuit design tools and are then fabricated at a commercial SOI foundry. The SOI process was chosen because it provides excellent electronic performance to 225C, with defined electronic functionality to 300C. Aside from providing higher temperature functionality and low power consumption, an ASIC provides a small package that will be easily incorporated into downhole tool electronics assemblies to provide an interface between the IntelliServ® network and customer MWD/LWD tools.

To date, several precursor circuits have been designed and fabricated. These include test chips to validate and better characterize the analog front end (AFE) portion of the circuit as a function of temperature. Two AFE test chips were built to test both the analog transmit amplifier chain and the analog receive amplifier chain. A diode test circuit was also implemented to allow testing of various simulation models. A third test chip allowed some of the analog blocks from previous chips to be individually characterized for better understanding of the correlation between the simulation models and the actual device performance. Additional modifications were made to test low power design rules.

Completed ASICs were bonded by commercial vendors in a ceramic package, without a lid, and were verified for proper operation on a Micromanipulator™ brand probing device (shown in **Figure 39**). A circuit board has been designed to allow access to each of the output pins on the chip while the chip is under power. Further diagnostic information is obtained by directly probing the interior test pads on the exposed die.

Software development. Software modules have been developed to control network function and provide monitoring of network health. The first of these programs, the Serial Bridge program, was provided for legacy 3rd party tools that have existing software control programs. These applications typically support direct serial connections between the tool and a support computer after it has been retrieved to the surface.

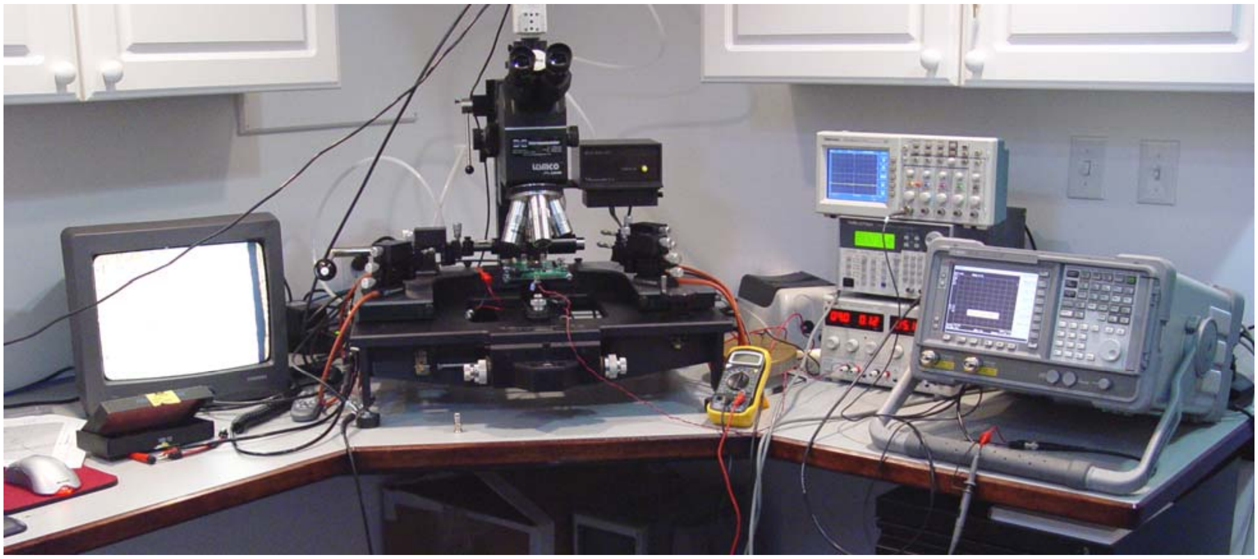
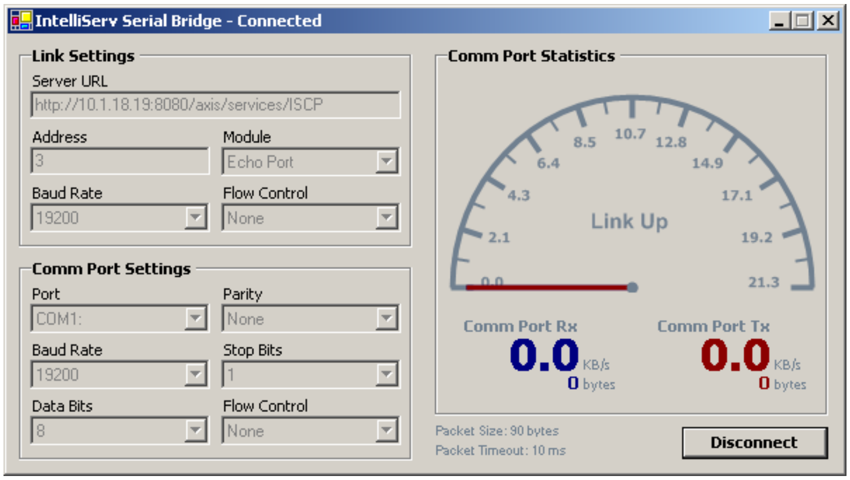


Figure 39. *IC probing station at Novatek*

The IntelliServ network is capable of supporting such applications directly while drilling. The Serial Bridge application provides a transparent bridge between the serial port of the client computer and the serial port of the tool port attached to one of the IntelliLinks. A screen shot of the software in operation is displayed in **Figure 40.** The program displays the current bandwidth utilization of the bridged serial port along with a "speed-o-meter" display indicating the current system utilization.



IntelliServ Serial Bridge - Connected

Link Settings

Server URL
http://10.1.18.19:8080/axis/services/ISCP

Address	3
Module	Echo Port
Baud Rate	19200
Flow Control	None

Comm Port Settings

Port	COM1:
Parity	None
Baud Rate	19200
Stop Bits	1
Data Bits	8
Flow Control	None

Comm Port Statistics

Link Up

Comm Port Rx 0.0 KB/s 0 bytes

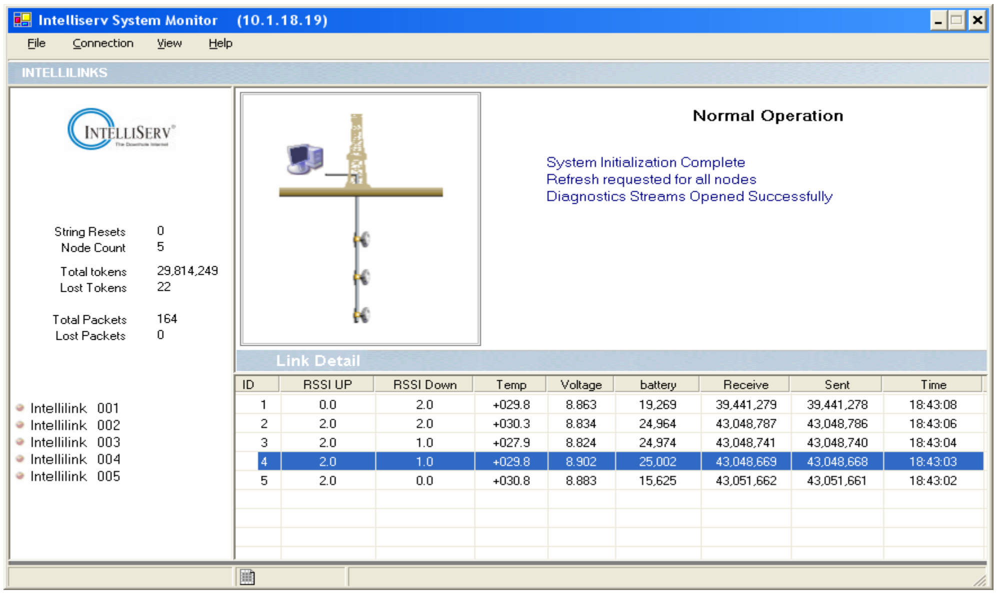
Comm Port Tx 0.0 KB/s 0 bytes

Packet Size: 90 bytes
Packet Timeout: 10 ms

Figure 40. *Serial Bridge program settings and statistics*

This program has been validated with two legacy applications, including the CoPilot® software from Baker Hughes Inteq (see below).

A second program, the System Monitor, enables viewing of the overall operation of the network. The purpose of the System Monitor is to display all of the relevant information or statistics from the IntelliServer or any of the IntelliLinks that are active in the drill string. A screen shot of this program is shown in **Figure 41**. Overall system information is summarized in the window at upper right and key information about each deployed IntelliLink is displayed in tabular format at lower right. The RSSI value is the gain setting (0-10) of the AFE in each direction, providing information about the attenuation in the string between adjacent Links. Also provided is a battery usage counter and a temperature recording at each Link. Additional statistical information can be displayed for any particular IntelliLink in a second window (not shown).



Normal Operation

System Initialization Complete
Refresh requested for all nodes
Diagnostics Streams Opened Successfully

String Resets 0
Node Count 5
Total tokens 29,814,249
Lost Tokens 22
Total Packets 164
Lost Packets 0

- Intellilink 001
- Intellilink 002
- Intellilink 003
- Intellilink 004
- Intellilink 005

ID	RSSI UP	RSSI Down	Temp	Voltage	battery	Receive	Sent	Time
1	0.0	2.0	+029.8	8.863	19,269	39,441,279	39,441,278	18:43:08
2	2.0	2.0	+030.3	8.834	24,964	43,048,787	43,048,786	18:43:06
3	2.0	1.0	+027.9	8.824	24,974	43,048,741	43,048,740	18:43:04
4	2.0	1.0	+029.8	8.902	25,002	43,048,669	43,048,668	18:43:03
5	2.0	0.0	+030.8	8.883	15,625	43,051,662	43,051,661	18:43:02

Figure 41. *System Monitor program*

System testing

A typical drillstring network contains 500 lengths of drill pipe, 50 lengths of drill collars and heavyweight drill pipe, and a variety of specialty tools and subassemblies. Wiring so many components together in serial dictates that each component must be extremely reliable. This has required a prudent step-by-step development of the network with continual feedback from bench and field tests. The system is now approaching the level of reliability needed for commercial operation.

Verification of 1000 ft transmission distance. Initial tests utilized shortened pipe "joints" that were created by welding Grant Prideco XT57 box and pin tool joints back to back. 34 ft of the transmission line was coiled inside the shortened segment to maintain full electrical equivalency of 1000 ft. This enabled testing of a 30-joint simulated system in the 100-foot well test that was available at that time.

Figure 42 shows the simulated joints used in the test. An 8-1/2 inch bit was attached to this string to provide a suitable signal to transmit through the string. A bit sub was equipped with an accelerometer and an FM modulator to capture the random drilling sounds and send them to the surface. This rudimentary "smart bit," shown in **Figure 43**.) was the first-ever demonstration of MWD at high data rate. The accelerometer signal was viewed on an oscilloscope and was converted to audible sound, and the sounds arising from various drilling modes were readily distinguished from each other. To simulate rig floor operations, short joints were added to the drillstring during the course of the test. To assist in verifying proper operation of the prototype segments as they were added, an electronic circuit was built to detect the carrier signal and actuate a light verifying joint makeup.

Figure 42. *Prototype 5-7/8" XT57 "Joints" used in drilling laboratory testing*

Figure 43. *Rudimentary Smart Bit Prototype*

Testing of full length pipe components. Following successful operation in the shortened joints above, network components were installed in full-length pipes. At first, 3 full length pipes were assembled and tested in the 100-foot well in Provo, Utah. A 1,000-foot well was then drilled nearby, and a full string of 30 full-length pipes was tested. again with analog transmission of drilling sounds. Additional pressure and vibration diagnostic tests (described above) were used to validate stringelectrical function.

Development and testing of interfaces with 3rd party tools. The IntelliServ network is capable of providing electronic connectivity to virtually any downhole or surface-deployed tool. Geometrical and functional differences between varying tools, however, necessitate a certain amount of tool customization in order to connect these tools to the network.

Technical collaborations with three major oilfield service providers has yielded substantial progress toward completion of physical and logical interfaces between the IntelliServ network and existing MWD and LWD tool suites. In two of these cooperative endeavors, complete interfaces were developed and were sent to various field test locations during the latter part of the development effort (see below). The first successful interface was built for Baker Hughes Inteq's (BHI) CoPilot® tool. This tool delivers real-time drilling dynamics and performance information to a rig floor display, providing data to the driller for enhanced control of the drilling process. The tool measures stresses, pressures and vibrations simultaneously at a high data rate (1000 Hz).[v] Once this interface was developed, extension of the network to other similarly connected tools was readily achieved. BHI technical personnel have provided excellent cooperation and technical collaboration.

As part of these development efforts, tools from each of the participating providers were shipped to Provo for benchtop system validation, followed by qualification testing in one of the Provo test wells. Interface subs were assembled onto each tool and continuous statistics were acquired on the benchtop from the interface subs. Once the channel was verified through the interface sub on each tool, the MWD tool was then queried. The tool provider then verified any tool-specific communications software.

Following successful benchtop verification, the sub and tool assemblies were deployed at the Provo drill site in a cased, 12-inch diameter, 1000-ft well. Each tool assembly was made up to an 8-1/2 inch bit and this assembly was tripped in the well. The channel and tool under test were checked for proper operation as described above. Upon successful verification of this assembly, drill collars and 5 inch IntelliPipe joints were then added to the test strings until the desired test configuration was achieved. Frequency sweeps (for line characterization) were requested from an IntelliLink board in the interface sub to verify competence of the transmission line as joints were added to the string, and data transmission statistics were periodically monitored. Data bursts from the tools were also recorded.

Once each string was fully tripped in, flow and rotation were started. Setpoint conditions varied, depending on the tool, but generally included approximately 1000 psi, 250-350 gpm, and 30-80 rpm. Data was collected from for several hours from each tool. Vibration data was additionally collected from accelerometers inside the IntelliLinks. Once the objectives of the test were successfully met, the system was powered down remotely and the test was concluded.

Preparations for field tests. Development to date has focused on two pipe diameters: 5-7/8" drill pipe, primarily used for premium offshore and extended reach drilling applications, and 5" drill pipe for a wider variety of applications including land wells. By the end of 2004, approximately 24,000 ft of 5" normal weight drill pipe had been built for laboratory and field tests and demonstrations. Approximately 5,000 ft of 5-7/8" drill pipe was modified and used in early testing. This will be upgraded to present the design. To provide for a top-to-bottom string, 1,500 ft each of 5" heavyweight drill pipe and 6-1/2" drill collars were wired. In addition to drill pipe, several other tools have been successfully wired, or are in the process of being wired, in cooperation with several tool manufacturers. These include drilling jars, motors, kellys, kelly valves, reamers, and a few drill bit dynamics tools. Prior to shipping to well sites, all tubulars were qualified using methods described above.

Field tests. Field trials of the IntelliServ network began with simple systems and progressed step-wise to increasingly complex systems. This strategy was chosen to reduce the number of variables in each phase of the testing, to minimize risk, and to allow for development of manufacturing capabilities. Major steps have included: a) shallow wells with only Links and drill pipe in the string; b) deep (commercial) land wells with a partially wired string; c) commercial land wells with a fully wired string; and d) commercial land wells where communication was established with a 3rd party tool in the bottom hole assembly.

The initial field tests were in shallow wells operated by various test services, including the Rocky Mountain Oilfield Testing Center (RMOTC) near Casper, Wyoming (shown in **Figure 44**), the GTI-Catoosa test center near Tulsa, Oklahoma, and the Hughes Christensen "BETA" test facility near Beggs, Oklahoma. The latter facility was provided by Baker Hughes Inteq as part of a joint program to develop IntelliServ interfaces for their tool suite. These facilities offered wells in the 1,000 – 5,000 ft range and utilized 5-7/8" XT57 IntelliPipe.

Figure 44. *RMOTC Rig #1, Teapot Dome near Casper, Wyoming*

These shallow well field tests were used to demonstrate network functionality and provide periods of extended use and handling for the wired tubulars. Tests included multiple trips of the pipe in and out of the wells, cementing operations, jarring cycles, and highly erosive flow levels.[vi,vii] Up to 3200 ft of 5-7/8" wired pipe was deployed at any given time. Copper-based, Teflon®-based, and zinc-based thread compounds were all tested during these shallow well tests to demonstrate the independence of the system from thread compound composition.

Subsequent to the shallow well tests, wired tubulars were sent to a series of consecutively drilled development wells operated by BP America, Inc. Each well required 5" IntelliPipe, 6-1/2" wired jars, 5" wired heavyweight drill pipe, and 6-1/2" wired drill collars. These wells averaged approximately 14,000 ft depth, had bottom-hole temperatures in excess of 100 C, and were mostly vertical. They were all drilled with a rig outfitted with a top drive[3]. In these wells, 3rd party tools such as the BHI Copilot® were deployed. These tests are discussed in greater detail below.

RESULTS & DISCUSSION

Improvements to transmission line components

Modeling of the transmission line, coupled with laboratory testing of the components under a variety of simulated conditions has led to substantial improvements to the electrical characteristics of the line over the course of the project. Improvements have been made to bandwidth, attenuation, and dispersion. **Bandwidth** is a measure of the range of frequencies that the network system can utilize for data transmission. **Attenuation** is loss in signal strength, expressed as a ratio of output to input. It is usually given in decibels or dB, which is defined as 10 times the base-ten logarithm of the ratio of the output power to the input power. It is usually more convenient to measure voltage than power, and for a fixed impedance, power is proportional to voltage squared, so attenuation, in dB equals $20 * \log (V_{out}/V_{in})$. As illustrated previously in Figure 18, attenuation varies with frequency.

Dispersion is the measure of signal integrity or distortion. The most familiar example of dispersion is found in optics, where a prism breaks a beam of light into its component colors. This happens because the speed of light in glass varies with its frequency. A high-quality camera lens is designed with multiple components to correct for dispersion, so that all components of a colored image come to a focus at the same point. In an electrical transmission line, signals of varying frequency will travel at different velocities. In order to send a large amount of information over a transmission line, a large band width must be utilized – thus various components of the information will be encoded at different frequencies. If these components travel at different velocities, then the information will be smeared out with increasing distance, and information will be lost. Dispersion is most frequently characterized as group delay, in seconds. It is the negative of the derivative of the phase (radians) with respect to angular frequency (radians/sec). When the phase is linear with frequency, the slope is constant, so the group delay is constant and there is no distortion or dispersion of the signal.

Several design variables have been found to influence the above electrical characteristics of the unique IntelliServ transmission line, including geometry, proximity of mating IntelliCoils, ferrite composition, processing parameters, and impedance balancing of the electrical circuit comprising the IntelliCoils and the coaxial cable. Modifications to these essential variables have widened system bandwidth, decreased system attenuation, and decreased system dispersion**.** **Figure 45** shows the improvement in the electrical characteristics of a single wired pipe over the course of the project, in

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[3] Work with this rig and operator is expected to continue at least into 3Q 2005

terms of forward gain and bandwidth. As shown, early prototype pipes suffered from low gain (high attenuation) and small bandwidth; later advances improved these substantially.

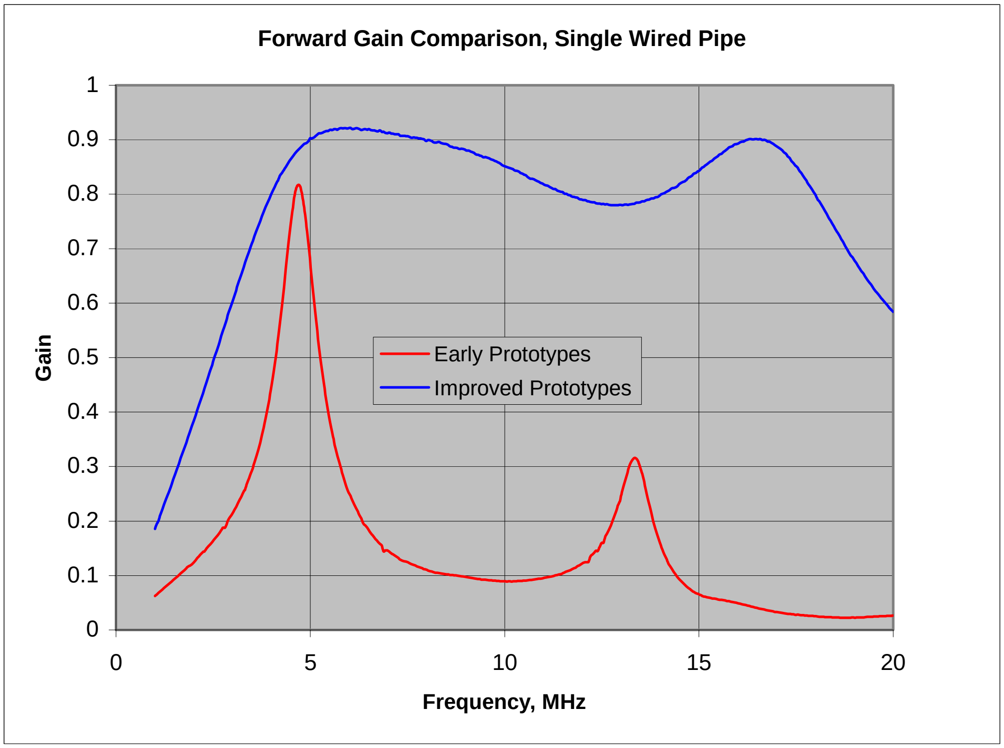


Figure 45. *Improvements to frequency response of different wiring components*

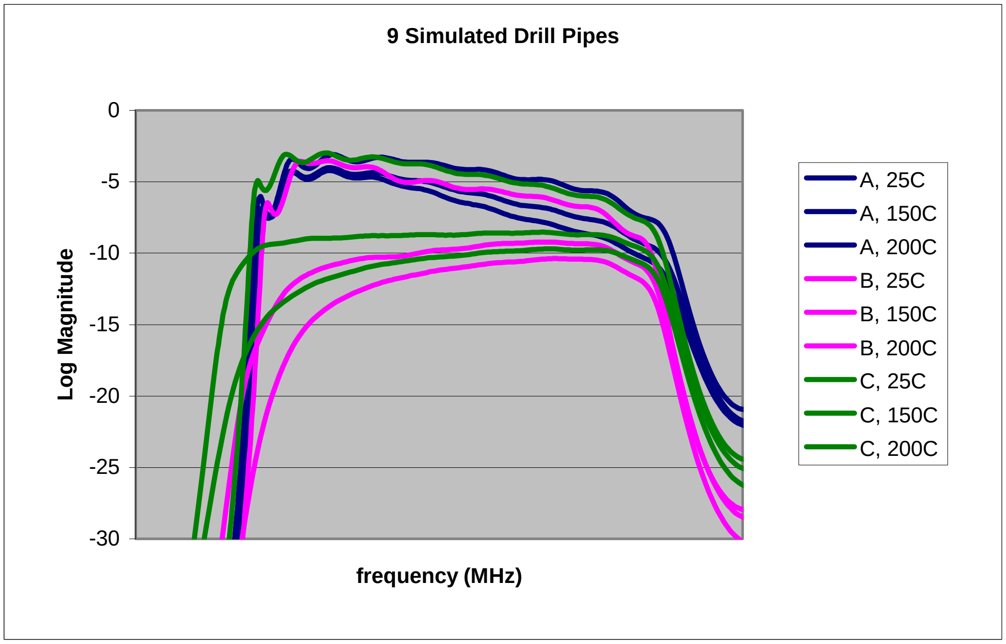


Figure 46. *Influence of temperature and IntelliCoil design on frequency response of 9 "compact" drill pipes*

It should be noted that the data presented here is taken at room temperature. If temperatures are elevated, further optimization must occur. **Figure 46** shows the effect of temperatures up to 200C on various embodiments of the transmission line. In this test, nine "compact" pipes (similar to the system shown in Figure 20) are represented. As can be seen, configuration A shows superior temperature stability to configurations B and C

Knowledge of how temperature affects transmission line characteristics not only helps optimize individual component design, but it also is an important element in overall design of an IntelliServ drill string. In particular, spacing of IntelliLinks along the drill string can be adjusted for the predicted temperature profile of the well. IntelliLinks may be deployed more frequently in the deeper, hotter portions of a drillstring to compensate for increased system losses at temperature, and Links may be deployed more sparsely in cooler, up-hole portions of the string.

The above improvements have yielded great dividends in the field by increasing the range of passive transmission of the system, thereby reducing the number of Links required. In an early embodiment of wired drill pipe, average attenuation per pipe segment was 1.2 dB (76% power transmission) at room temperature. Subsequent designs achieved approximately 0.4 dB attenuation (91% poweer transmission.)

Improvements to electronic components

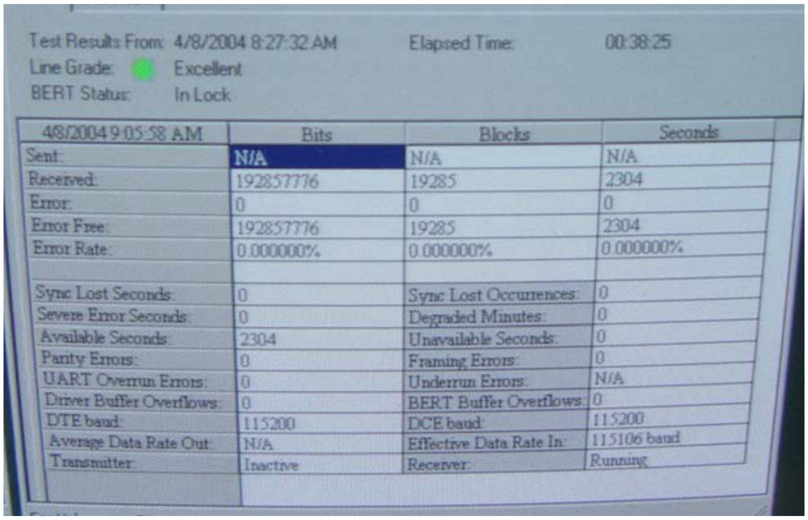
Catoosa System. The Catoosa system provided critical system diagnostic service in the early stages of the project, including deployment during the first two field tests in BP wells. However, the temperature rating of this prototype was exceeded as the network was deployed deeper in the wells. It was replaced for field operations by the Topaz system in the third BP field well. Catoosa links are still used at the Provo Test Site to provide diagnostic frequency sweeps.

Topaz System. Topaz boards have been demonstrated in the laboratory to effectively communicate at 115.2 kbits/sec at room temperature through a 5,000-foot hardware IntelliPipe simulator (see Figure 19). Under field conditions, this transmission distance has been shown to be on the order of 2000 ft. Some uncertainty still exists about the maximum separation distance between IntelliLinks™ for the TOPAZ system; this will be refined through further field testing.

The data rate offered by the Topaz system allows useful data to be transmitted from many existing MWD/LWD tools. However, two applications presently under development require very high data rates. This increased requirement validates the original project goal of 1 Mbit/sec.

Further testing of the Topaz boards in an atmospheric chamber has shown that the boards can maintain proper functioning for extended periods at the 150C design temperature. Several printed circuit assemblies have been subjected to thermal cycle testing and have not experienced any failures to date. A Topaz power supply board has logged the most hours so far without failure (approx. 2,000 hrs.)

Figure 47 shows a typical screen shot during BERT testing of Topaz boards at temperature. As shown, this testing system offers extensive analysis of the effectiveness of data transmission at the selected speed and transmission distance.



Test Results From: 4/8/2004 8:27:32 AM
Elapsed Time: 00:38:25
Line Grade: ● Excellent
BERT Status: In Lock

4/8/2004 9:05:58 AM	Bits	Blocks	Seconds
Sent:	N/A	N/A	N/A
Received:	192857776	19285	2304
Error:	0	0	0
Error Free:	192857776	19285	2304
Error Rate:	0.000000%	0.000000%	0.000000%

Sync Lost Seconds:	0	Sync Lost Occurrences:	0
Severe Error Seconds:	0	Degraded Minutes:	0
Available Seconds:	2304	Unavailable Seconds:	0
Parity Errors:	0	Framing Errors:	0
UART Overrun Errors:	0	Underrun Errors:	N/A
Driver Buffer Overflows:	0	BERT Buffer Overflows:	0
DTE baud:	115200	DCE baud:	115200
Average Data Rate Out:	N/A	Effective Data Rate In:	115106 baud
Transmitter:	Inactive	Receiver:	Running

Figure 47. *Close-up of BERT software collecting error statistics*

Representative results of the BERT test, run while the test boards were operating at 150C temperature and transmitting over the simulated pipe (with the "pipe" at room temperature), are as follows:

Elapsed Time	Distance	Bit Error Rate	Bits Sent	Bit Errors
23:54 hrs	1 Mile Spools	0.043028%	7,190,276,944	3,093,860
7 days	1 Mile Spools	0.014909%	50,552,891,154	7,538,014
21:59 hrs	1 Mile Spools	0.010409%	6,627,228,832	689,808
23:46 hrs	¾ Mile Spools	0.000074%	7,162,794,048	5283

As can be seen, the bit error rate for the medium temperature Topaz system over 1 mile is well under 0.04%, and for ¾ of a mile the bit error rate is extremely low. It is worth noting that error-free or very low error transmission at room temperature of the Catoosa versions was limited to about ¼ mile. The Topaz revision of electronics thus offers a substantial range improvement over the Catoosa systems.

During initial deployment of the Topaz system to BP well #3, some weaknesses in the low level network protocols that had been implemented in the Topaz firmware and in the IntelliServer software were identified, and the firmware and software were updated to correct these defects. Modifications to the Topaz firmware are still under way to make the software more robust, and certain of these modifications are have been implemented in the Pearl system. Field test conditions near 125 degrees C have corroborated the above medium-temperature laboratory testing at least to some extent (Catoosa boards previously shut down at these temperatures). Operation of the Topaz system has been successfully demonstrated with two partner tools – the CoPilot® from Baker Hughes Inteq and the "Drilling Research Tool" (DRT®) from ReedHycalog.

Opal System. The Opal system has been completed and has fulfilled its role as a precursor to the Pearl system. A bench-top Opal system has been used by a development partner to bench test

IntelliServ-ready tools that require a 1 MBit/sec data rate. It is not intended to be operated in a down-hole environment.

Pearl Project. The initial prototype of the Pearl system has been created as an oversized printed circuit board. This has facilitated engineering development and granted access to circuit probe points through the use of multiple debug and probe ports. Additionally, it was designed to be able to handle several footprint variations for many of the component parts. This was necessary to qualify alternate suppliers of components to 170 degrees C.

To date, bench-top operation of the PEARL prototype, including network operation between boards, has been successfully verified. Further development is focused on qualifying components for the desired temperature rating. It will first be deployed downhole by the partner that is now using the Opal system for bench-top development of tools.

Sapphire Project. The infrastructure needed for the Sapphire project is being developed concurrently with the precursor systems discussed previously. A high-temperature test lab has been built and is being exercised on initial test chips to develop the test capabilities required for the system. It is expected that the Sapphire system will become available in 2006.

Summary of field trial results

RMOTC (Feb 2003). Over a hundred full-scale joints of 5-7/8" IntelliPipe were tested in a 4500 ft well at the Rocky Mountain Oilfield Testing Center near Casper, Wyoming. This test included 10 joints of heavyweight drill pipe, 106 joints of normal weight drill pipe, and 5 IntelliLinks™. IntelliLinks™ employing Catoosa boards were dispersed in the string at approximately 1000-ft intervals. Communication with the drillstring was established during drilling and reaming operations totaling approximately 400 and 600 ft respectively. During this test, a simple bi-directional high-speed IntelliServ network was demonstrated with 5 IntelliLinks communicating at 2 Mbit/s raw (backbone) data rate.

BETA (Q3-Q4 2003, Q1 2004). Approximately 3200 ft of 5-7/8" wired pipe was sent to Baker Hughes' BETA test facility in Oklahoma for extended testing. At the first well where the pipe was to be deployed, a non-wired BHA was tripped in the well (wired BHA components were unavailable at the time of the test), followed by a string of approximately 2500 ft of IntelliPipes and IntelliLinks. Only two IntelliLinks were deployed, approximately 1440 feet apart. The well had multiple doglegs, the largest being 8 degrees/100 ft.

During the first two days of the test, each IntelliLink sub (Catoosa version) was polled repeatedly by the network to verify proper communication. Bi-directional communication through the drillstring was established during tripping operations via a small portable hand-attachable sub (see **Figure 48**) that connected the top joint in the well to the surface computer. During drilling operations, bi-directional communication was established using a data swivel deployed just below the top drive. Quality of data during digital transmissions was validated by the absence of checksum and/or "handshaking" errors.

Figure 48. *Portable sub for connecting the network during Tripping*

Figure 49 shows attenuation vs. depth for two sections of drill string that were added sequentially above two separate Links. (The second link was added after 16 pipes had been connected above the first). As shown, the two sections had nearly identical attenuation, measuring -0.431 and -0.425 dB per joint, respectively. This attenuation was consistent with that measured in the laboratory.The pipe and Links saw approximately 10 drilling hours with monitoring of the network. The pipe was then left overnight hanging in the slips in continuous data transmission mode. A raw data transmission rate of 2 Mbit/sec was achieved without any type of data error over the entire 2 day period. Various network features were exercised during the test, including time-synchronous data transmission from the triaxial accelerometers mounted in each IntelliLink.

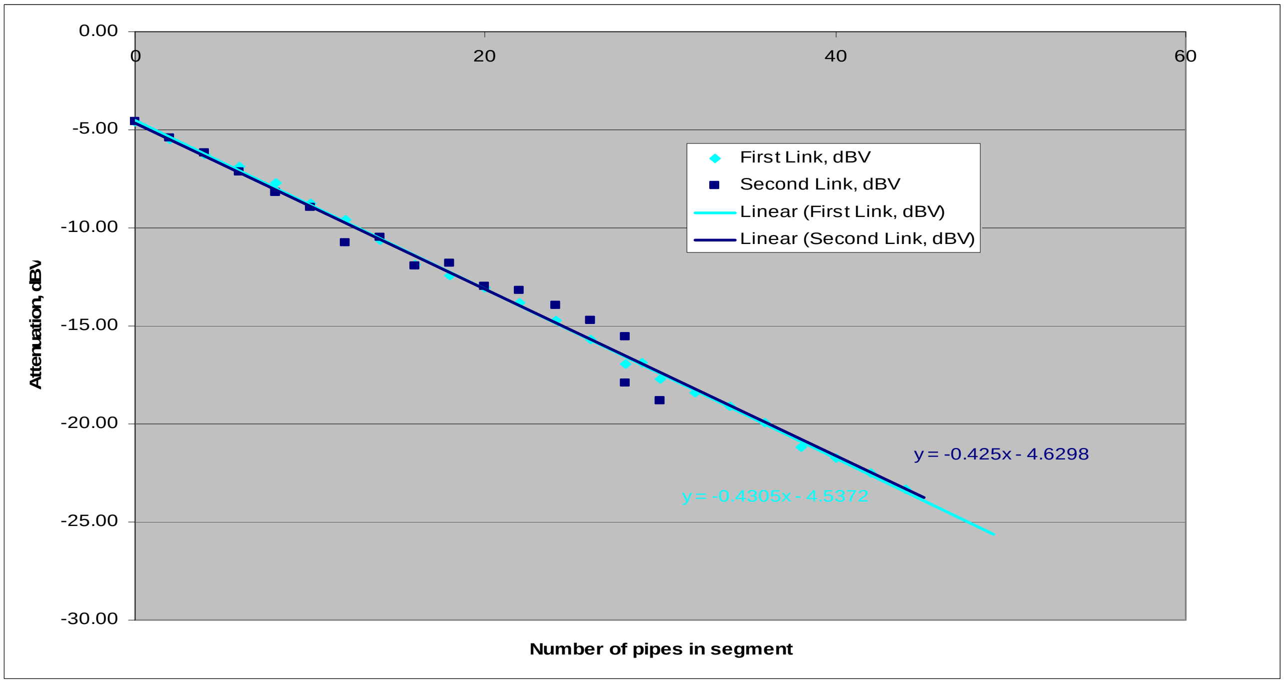


Figure 49. *Attenuation characteristics for IntelliPipe in first BETA well*

After two days of monitoring the string, the surface computer was disconnected and the IntelliPipe and IntelliLinks were left with the operator for further use, as part of the ongoing robustness test. Five wells were drilled using this pipe over the next several months. Total circulating and rotating hours logged by the driller added to 194.99 and 113.31 hours respectively. In addition, 27 total trips were counted.

During the test period, the pipe was used for cementing operations to plug back approximately 3,000 ft sections of two wells without encountering any difficulty. An erosion test was also performed with one joint of IntelliPipe, wherein 1000 gpm of approx 8% solids content mud (1% sand) was pumped through the pipe for 100 hours. Inspection of the pipe showed no damage to internal transmission line components and no change to its electrical characteristics. The pipe was laid down in early March of 2004 after the last well was drilled, and the pipe was shipped back to IntelliServ for visual and electrical analysis.

Visual inspection indicated that the transmission line components (connector rings and cables) were in generally good condition. However, electrical examination of the pipes revealed several pipes with an electrical connectivity fault. This fault was traced to a flaw in the design of the connector rings that allowed electrical connectivity to be interrupted during makeup or break out of the connection. Seventeen of the 100 pipes exhibited this failure mode. This observation led to a simple design change in the ring assembly. A few pipes that exhibited excessive damage to the secondary shoulder of the tool joint also sustained damage to the connector rings. All cables inside the pipes were intact and showed no damage that could be detected, either by visual examination or by electrical testing.

BP #1 (Jun 2004). Approximately 6400 feet of IntelliPipe and IntelliLinks were deployed in this first full-scale commercial well. Since the total depth (TD) of this well was greater than the footage mobilized to the site, the IntelliPipe was kept at the top of the drillstring to enable communications with the surface to be maintained. IntelliLinks were deployed with a conservative spacing of 600 ft.

Three initial difficulties were experienced with surface equipment: a) cables connected to the data swivel were subject to in-band (high frequency) electrical noise, which required additional effort to provide adequate isolation; b) top drive operation during tripping operations occasionally led to entanglement and breakage of surface cabling, which required a change in cable connection procedures; c) mis-stabbing of the data swivel into the drill pipe by an inexperienced operator caused substantial mechanical damage to the threaded connection and damage to the IntelliCoil (see **Figure 50**). Once these surface difficulties were overcome, successful transmission was achieved at high data rates between the surface and downhole Links.

The prototype IntelliLink electronics modules (Catoosa Links) used in this test were limited to about 85C. This limit was exceeded midway through this well. When mud flow was stopped, the hole would warm up, and a Link would quit. When mud flow resumed, cooling the Link, it would resume operation. All Links were visible to the network during the test, excepting the lowermost two, which had exceeded their temperature rating. Approximately 500 drilling or flowing hours were logged on the pipe during this test. In addition, successful field application of TDR to wired drill pipe was demonstrated.

Figure 50. *Stabbing Damage to Data Swivel*

BP #2 (Jul – Sep 2004). Early in the second commercial well a CoPilot® tool provided by Baker Hughes Inteq was inserted into the wired portion of the drillstring, just above the bottom hole assembly (BHA). This tool successfully transmitted real-time drilling data for a short period of timethrough approximately 3000 ft of IntelliPipe and IntelliLinks. Nearly two weeks of intermittent data transmission from the tool were tallied over the course of the test. Intermittencies were due to several communication difficulties between the Inteq tool and the network Link. Some errors were noted to occur as the recorded annulus temperature approached 79-80C, which is near the limit of operation for the circuit boards used in the test. The errors disappeared as the temperature dropped below those values. Notwithstanding the intermittent nature of the communications, the test was considered a success and the tool was removed from the string when its batteries were depleted.

The Inteq tool was replaced by an IntelliLink for the remainder of the well. This Link, along with 3 others that were to be deployed in the deepest locations in the well, was outfitted with a Catoosa style circuit board that had survived testing for a short time at 100C (even though the components were only rated for 85C). Unfortunately, this effort to selectively screen out higher temperature rated circuit boards failed to produce improved temperature reliability, and these Links failed to respond consistently. Subsequent evaluation of the circuit boards used in the test showed that some of them failed due to breakage of solder joints due to thermal expansion. Out of just over 9,000 ft of IntelliPipe deployed in the well, the uppermost 6,900 ft were visible to the network. Other problems encountered in the second well include connector damage to surface cabling and one electrical failure in a drill pipe, due to a manufacturing process error. Over 400 drilling hours were logged on the pipe during this well.

BP #3 (Oct – Nov 2004). Temperature concerns with the Link circuitry were allayed in the third commercial test well by the introduction of a higher temperature Link design (Topaz revision).

These new boards also allowed deployment of Links every 2000 ft in the well, as opposed to the 600-1500 ft achieved with earlier circuit boards. Topaz circuit boards were deployed with confidence, after having been previously tested for extended transmission range (up to a mile) and thermal stability in the lab (to 150C) for durations on the order of 2000 hours.

This well also saw the introduction of wired BHA components, including jars, reamers, heavyweight drill pipe, and drill collars. These components provided everything necessary for a complete top-to-bottom (or near bottom) drilling network. With a complete wired string in place, the drilling contractor shipped all of its own (unwired) pipe to another site and began using IntelliPipe exclusively. Only the motor, air hammer, and a few special tools at the bottom of the drillstring were not wired.

Following an initial air drilling section in the well, the Baker Hughes Inteq Copilot tool was deployed in the string, this time powered by a mud turbine generator. A Topaz Link was deployed in the tool assembly to provide the network interface to the tool and was powered by the same generator. This power source proved to be detrimental to the performance of the Link because it allowed a marginal power condition to occur as the generator spun down each time mud flow stopped. This abnormal power condition was not anticipated in the prototype Topaz configuration, but this condition has since been resolved by a programming change. Approximately 24 hours of data transmission from the Inteq tool were logged through one drill collar, 25 heavyweight drill pipes, and a jar before these problems surfaced.

Other problems encountered in this well later led to removal of all Links from the string. These problems include loss of a circuit board due to thermal expansion of the packaging material (since resolved), loss of electrical ground on an IntelliCoil due to a manufacturing error (process now better controlled), and breakage of several IntelliCoil rings in IntelliLink pipes. This latter failure was a result of 60+ jarring cycles experienced by these pipes during a stuck pipe incident late in the well. Design improvements have been made and confirmed through further jar testing to prevent this mode of failure. Approximately 600 drilling, reaming, and circulating hours were logged on the IntelliPipe in this well.

SUBSEQUENT BP WELLS (2005). Three further BP wells have been drilled with the IntelliServ network since December 2004. All three wells were drilled to measured depths exceeding 12,500 ft, using only intelligent tubulars in the string (with the exception of occasional use of an unwired downhole motor). Typical rotary drilling assemblies were used in the wells, including 5" IntelliPipe, 5" IntelliHWDP, 6.5" IntelliJars, and 6.5" IntelliCollars. In the fourth well the ReedHycalog DRT tool was deployed within the drill collar portion of the bottom-hole assembly (BHA). This tool successfully transmitted data for 36 hours during a high-shock section of the well that was drilled with an air hammer. (Most MWD and LWD tool providers will not allow their tools to be deployed while drilling with air.)

In the fifth well network communication was initiated at 600 ft depth at the start of the 12-1/4" hole section, and it continued through the remainder of the well. The network successfully provided high-speed, real-time telemetry services throughout the drilling program. During part of the drilling program, an IntelliServ-ready BHI OnTrak® tool was deployed in the BHA. The OnTrak® tool provides directional survey, drilling dynamics and basic formation evaluation data. Data from this tool and from Links in the network was sent live via satellite to engineers in Provo and Houston. While drilling the fifth well, the IntelliServ network logged more than 800 hours mean-time reliability, with communication

rates of 115,000 bits per second. Nearly 100% downhole reliability of downhole equipment was observed for the duration of the well.

A sixth well has just been completed. In this well, the IntelliServ network system provided competent network data to the very end of the well and reached a record operational depth of 13,245 feet. It is worth noting that the same telemetry tubulars used in the sixth well had been used to drill the four previous wells for BP. Combined, the IntelliServ network has accumulated over 3,500 operating hours on these test wells in extremely harsh conditions, including very high shock air drilling. IntelliServ tubulars have now been used to drill over 60,000 feet of hole in Oklahoma, demonstrating handling characteristics equal to standard drilling tubulars with high mechanical and electrical reliability.

Further field tests and demonstrations are planned during 2005. BP America intends to continue drilling with the IntelliServ drillstring at least into 3Q 2005. In addition, a string of pipe has shipped to another operator who intends to use the system for several wells. This latter well will help demonstrate IntelliServ's ability to simultaneously service multiple sites.

With the completion of a sixth well with BP America Inc, the long-desired industry goal of high speed, real-time drill string telemetry has been achieved. In the process of drilling these test wells, Novatek has not only been able to substantially harden the system against real-world conditions, but it has also been able to develop personnel that will be part of a well-trained field service and support organization as the system becomes commercialized. Further, as indicated above, substantial progress has been made to demonstrate connectivity with a variety of 3rd party down-hole tools. Baker Hughes Inteq has shown substantial leadership in preparing IntelliServ-ready down-hole services. Several additional service companies are now making their tools IntelliServ-ready.

COMMERCIALIZATION PLANS

Discussions are now underway with selected E&P partners to introduce the system commercially. This phase includes further field tests and demonstrations to build a customer base, phasing of production efforts from Novatek's prototype facility into new facilities in Provo, building and distribution of increasing numbers of full strings, increasing the size and skill level of IntelliServ's field service organization, and substantial initial marketing efforts. To date Novatek and Grant Prideco, the private commercial partners in this venture, have invested over $50 million in the technology, including funding of research & development and additional capital investments. Both continue to be committed to invest the needed technical and business effort and the capital to carry the technology to successful commercialization.

Commercial applications of the technology

The full value of the IntelliServ network is only realized when it enables communication with useful downhole tools. These include a myriad of existing 3rd party tools MWD and LWD tools that can be readily interfaced via the Serial Bridge. Other tools that will use the heretofore undreamed of capabilities of the IntelliServ network are already on the drawing boards. Several of these new and existing applications are described below.

Improvements to Energy Asset Value - Geosteering, Look-ahead/Look-around Seismic. The IntelliServ network will provide the greatest potential benefit by improving asset characterization and productivity. The high-speed network enables a better understanding and characterization of a reservoir via increased flow of downhole information during drilling , including real time formation characterization and in-well seismic surveys. Many of these applications require copious transmittal of copius amounts of data to the surface in real-time, or in near-real-time. The enhanced understanding provided by the network allows optimized well placement (e.g., geosteering), acceleration of the proving process for reserves, and an accelerated production curve. It also decreases the risk of missing or overlooking pay zones. The high-speed network is an enabling technology for even more sophisticated diagnostic tools than are currently on the market – tools for discovering subterranean resources and more accurately assessing and ensuring the value of the asset. With better asset characterization while drilling, production from an asset can be increased and fewer wildcat wells must be drilled, reducing both cost and environmental impact.

Optimized Casing Point - Drill Bit Seismic. Drill bit seismic has been used with success to enhance the drilling process by aiding drilling personnel to more accurately choose casing point and to plot bit depth.[viii] Presently, however, the technique is limited by bit type, water depth, well deviation, and drillstring components used. These limitations are primarily due to the fact that the pilot signal is presently characterized by measuring vibrations transmitted mechanically through the drillstring.[ix] The IntelliServ network improves drill bit seismic practice by providing a way of transmitting to the surface a more accurate representation of the pilot signal, or simply by providing a much more accurate incident time (T0) for correlation with the received signal.

Decreased Formation Damage and Improved Drilling Speed via Underbalanced Drilling. Mud pulse telemetry cannot be used in many air drilling or underbalanced drilling applications (UBD) because a pulse cannot be efficiently transmitted through a highly compressible fluid. The IntelliServ technology is independent of fluid type and can therefore be used to improve the safety of, and increase the use of, underbalanced drilling, managed pressure drilling, and air drilling technologies, which can be used to both increase drilling speed and decrease formation damage.

Other Improvements to Drilling Efficiency – LWD, MWD, Bit Dynamics, Drillstring Dynamics. Combined with existing LWD and MWD tools, the IntelliServ network enables improvements in the overall drilling process that will result in faster well drilling, thereby reducing overall well costs. With the high-speed network, real time bit dynamics or drillstring vibration data can be transmitted and used to improve bit life and reduce bit trips. Similarly, improved communication with the downhole drilling assembly can allow more efficient drilling by detecting and avoiding stick-slip, bit whorl, bit reversal, and excessive vibration of the BHA. Increased feedback and control of the drilling process will help to prevent overshoot into adverse formations, which in turn can reduce contamination of the well or loss of the resource.

The ability of the network to provide multiple measurement sites along the length of the drill string enables equivalent circulating density (ECD) measurements to be obtained by annular pressure readings, not just at the bottom of the drillstring, but also at potential problem zones along the bottom hole assembly and all along the drillstring. Links with annular pressure transducers may be placed at any point in the string, allowing differential measurements between any pair of Links. This provides a more detailed picture of the condition of the wellbore, revealing zones of localized flows into or out of the wellbore, helping to predict incipient caving of the wellbore and/or damage to the wellbore, or pinpointing cutting buildup or pack-off. Since this information is delivered in real time by the IntelliServ network, opportunities to take timely remedial action are greatly improved. Similarly, a more detailed understanding of the mechanical state of the drillstring may be provided via distributed weight-on-bit (WOB) and torque-on-bit (TOB) data. Data regarding frictional loading of various segments of the drillstring could be determined by differential WOB and TOB data between two instrumented Links. This data could then be used to pinpoint problem spots and help to maintain optimal WOB and enhance drilling performance.

Improvements to Well Safety. Presently, mud pulse information from down-hole sensors can travel only at the speed of sound in mud, which is the same speed at which the kick travels. The much improved speed of data transmission over the wired pipe can provide nearly instantaneous kick detection, can substantially improve safety, and can decrease well control costs. Better pressure profiling along the length of the drillstring (from pressure transducers distributed at nodes in the network as described above) promises safer control of conventional drilling operations as well as of inherently more dangerous technologies like underbalanced drilling.

Commercial opportunities

The IntelliServ network has the potential to deliver value to all oil and gas drilling operations regardless of location or rig type. Furthermore, the technology can be expanded to well completion strings (including production tubulars and casing) or distribution systems (pipelines). Likewise, other industries outside of the oil and gas (and geothermal) industries, including water well drilling, horizontal drilling (e.g., under roads, rivers, etc), and mining, can apply the networking components to their particular needs. In short, the technology has application to all tubular drilling or piping systems – this is seen to be a truly revolutionary, game-changing technology.

It is likely that initial commercial introduction of the product will be paced by IntelliServ's manufacturing capacity. While capabilities ramp up, initial marketing efforts will focus on offshore oil & gas operations where expected returns are highest and downhole measurement services are already in use. A few such operations have already expressed interest in a commercial string – IntelliServ is truly on the verge of commercial operation.

Facilities

IntelliPipe and related IntelliServ products are currently manufactured in the Provo, Utah facility (

Figure *51*.) This facility is fully equipped and capable of all operations needed to manufacture IntelliPipe and related products. Current manufacturing capacity is 325 tubulars per month,

Figure 51. *Existing Provo, UT Facility*

facilitated by a staff of approximately 75 highly skilled technicians and professionals. The Provo facility also houses an exceptionally capable machine shop that provides prototyping, tool and fixture making, and a broad range of machining abilities that enhance the overall research, development and manufacture of IntelliServ products.

To support future growth, Intelliserv is building a new 72,000 sq.ft. manufacturing facility adjacent to the existing Provo building (**Figure 52**). This state of the art facility will showcase forward-looking manufacturing processes including automated tubular handling, advance systems, and machining practices unequaled in the industry today. This highly efficient facility will produce up to 20,000 tubulars annually. The design of this facility is such that it can be easily replicated to adjacent property to seamlessly accommodate additional growth. The building is scheduled to be complete and operational in Q4 of 2005.

Figure 52. *New IntelliServ manufacturing facility*

All manufacturing is performed to ISO quality standards and meets or exceeds all industry standards, requirements, and certifications. The best manufacturing systems will be in place including production control ERP (Enterprise Resource Planning) and comprehensive Quality systems.

Field Service organization

Onsite Technicians. As already mentioned, field trials have been utilized as a training opportunity for an on-site field service organization. Well sites to date have been over-staffed with a crew of 14 technicians, working equal rotations. As the number of active rigs expands, crew size will reduce as dictated by service needs.

Remote Operations Centers. A remote operations center has been established in Provo that can receive real-time data feeds from each operating rig. Ultimately it will be staffed 24 hours a day with support technicians or engineers. These support personnel monitor system performance and communicate via telephone with the rig crew if necessary. They also have access to the system's surface servers via satellite feed, allowing remote server maintenance and trouble shooting. Additional regional communication centers will be considered as warranted.

CONCLUSIONS & RECOMMENDATIONS

Based on the above data and discussion, the following conclusions may be drawn:

1) A high data rate communications system can be made sufficiently robust, reliable, and transparent to the end user to be successfully deployed for drilling of oil and gas.
2) A drilling network with user data bandwidth of at least 1 million bits per second can be built to service any practical depth of well using multiple repeaters (Links) with spacing between the Links of at least 1000 ft.
3) Communication can be established with a variety of existing 3rd party logging while drilling, measurement while drilling, and drill bit dynamics tools. There is no practical limitation to the number or type of tools that can be interfaced with the system.
4) Sufficient commercial applications and interest exist to ensure a very high likelihood of commercial success of the very high speed networking technology.
5) Novel wiring concepts used in creating a drill pipe transmission line can also be extended to use in complex down-hole tools like drilling jars and motors.
6) Commercially available electronics are presently inadequate for expansion of drilling tool intelligence. Present industry methods of screening components for high temperature application are insufficient for the long-term vision of smarter tools.

To continue improvement, ensure commercial success of the network, and ensure that long-term goals of improvements to the drilling process are realized, the following activities are recommended:

1) Continue field testing to learn what is needed to further field-harden components and to improve the utility of the system, and to determine component life (mean time between failures) and maintenance schedules

2) Intensify software development effort to increase the applicability of collected data to decision making and to enable better monitoring of system health

3) Continue development of SOI components to improve the reliability and temperature range of Link components

4) Develop improved power sources with extended temperature range to enable higher temperature application of the networking technology

Considering the above conclusions, one further conclusion can be drawn: U.S. Department of Energy participation in funding has been essential to the success of this project. Particularly in the early stages of the development effort, the risk was very high, and industry motivation to invest in such a giant leap forward was low. DOE vision and willingness to be involved in this technology has provided Novatek with the needed resources to get past the early stages and to develop the necessary technology. In light of the present financial commitment by Novatek, Grant Prideco, and other involved forward looking companies, and in the context of other possible industries affected by this technology, the monies invested by the DOE have certainly been highly leveraged towards a very successful endeavor.

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