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Abstract—A novel antenna design has been developed to detect fish implanted with full-duplex passive integrated transponder (PIT) tags. The antenna is constructed of lightweight flexible hose and measures 2.4 by 6.1 m, providing a substantially larger reading range than other PIT antennas. Herein, we describe its use in a small instream monitoring system to detect migrating smolts of steelhead (*Oncorhynchus mykiss*). During testing, the combined detection efficiency for the 2 arrays of antennas with the new design was 97%, which is comparable to efficiencies of standard antennas made with polyvinyl chloride or high-density polyethylene. The lightweight, flexible design of the new antenna affords relatively easy transportation and deployment compared with that of rigid antennas, and smaller crews and vessels are needed for its maintenance and deployment. The development of the flexible antenna has expanded the utility of PIT technology by increasing the scope of potential sampling applications to a wider range of habitats and environmental conditions.

Development and use of a large, flexible antenna to detect fish implanted with passive integrated transponder tags

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Passive integrated transponder (PIT) technology has been used to study a variety of terrestrial and aquatic organisms since its adaptation from the livestock industry in the mid-1980s (Thomas et al., 1987; Jackson and Bünger, 1993; Mills et al., 1995; Ballard et al., 2001; Bubb et al., 2002). Because of its long life, low cost, and low biological impact, the PIT tag has become an important tool in fisheries research and is used in studies of migration timing, behavior, and survival, as well as in comparisons of return rates of smolts and adults (Prentice et al.[1]; Prentice et al., 1990; McCutcheon et al., 1994; Peterson et al., 1994; Ledgerwood et al., 2004). Numerous detection site configurations and antenna designs have been used for such work, and as the technology improves, new configurations and designs have been developed (Lucas et al., 1999; Hill et al., 2006; Bond et al., 2007; Riley et al., 2010).

Early PIT antennas could sample small areas and were limited largely by transceiver capability. Development of the multiplexing transceiver subsequently decreased the size and increased the capacity of transceivers, which now can power and communicate with multiple antennas; however, general antenna design and construction has changed minimally through the years. Instream PIT antennas are traditionally constructed by using 10.2-cm-diameter pipes of polyvinyl chloride (PVC) or high-density polyethylene. The rigidity of these materials allows easy anchoring to stream beds and shorelines, and the pipe diameter provides a large air gap around antenna wires to reduce electrical resistance in submersed applications;

[1] Prentice, E. F., C. W. Sims, and D. L. Park. 1985. A study to determine the biological feasibility of a new fish tagging system. Annual report 1984–1985. U.S. Dep. Energy, Bonneville Power Admin., BPA Rep. DOE/BP-11982-1, 39 p. [Available from website.]

however, these features also present challenges, including bulk, weight, reduced mobility, and cost.

Many challenges associated with rigid antennas can be mitigated by decreasing the overall antenna size. It is common for rigid rectangular antennas to be built with dimensions no larger than 1.2 by 2.4 m, a size that compromises sample area out of necessity. Most research would benefit from larger antennas and detection ranges that maximize both sample area and efficiency associated with antenna construction and use.

In 2012, we modified the rigid antenna design to use a new PIT transceiver and system (IS1001 reader and IS1001 Multiplexing Transceiver System[2], Biomark Inc., Boise, ID) more fully, with improved functionality and performance, for use in experimental stationary and towed applications, similar to the sampling method described by Ledgerwood et al. (2004). The resulting prototype antenna, described herein, was made with small-diameter flexible hose instead of rigid construction materials and increased antenna size to an area of 2.4 by 6.1 m.

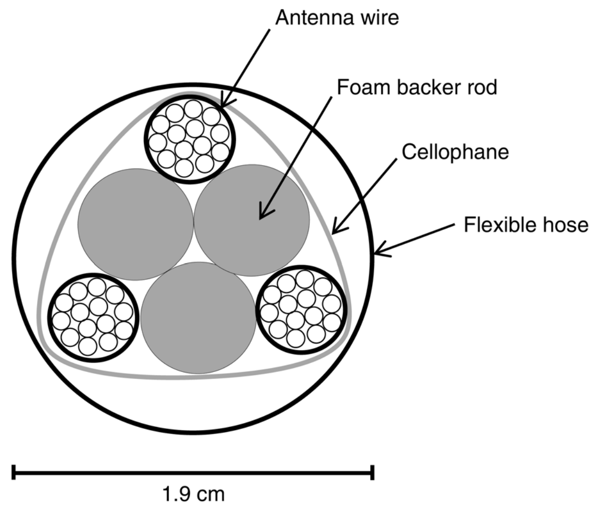


Figure 1

Cross-sectional view of the wire gallery of the flexible antenna developed to detect fish implanted with passive integrated transponder tags. Antenna wires (10 American Wire Gauge Litz wire) are placed between 3 foam backer rods (diameter: 6.5 mm) and wrapped in cellophane to hold the wires in position. The antenna is housed in a 1.9-cm-diameter, flexible PVC hose to create a waterproof barrier and to protect the wires from physical damage. This configuration was used in the antennas deployed for testing of their detection efficiency as part of a system to track migrating steelhead (*Oncorhynchus mykiss*) in Abernathy Creek, of Washington, in 2015.

Materials and methods

Antenna description

The IS1001 Multiplexing Transceiver System was used to power and communicate with the antennas. This system required a dedicated IS1001 reader for each antenna. To operate multiple antennas as an array, we used the multiplexing function of the IS1001 Master Controller (Biomark Inc.). According to the manufacturer, exciter circuitry on the transceiver system was designed to operate antennas as large as 1.2 by 6.1 m (Biomark Inc.[3]). However, after testing various components and configurations, we were able to construct an electronically stable 2.4-by-6.1-m antenna with the capability to detect all sizes of full-duplex PIT tags commonly used in the Columbia River Basin. To produce a detection field this large, we connected the IS1001 reader directly to the antenna windings to maximize current output.

The antenna was constructed by using 3 turns of 10-gauge Litz wire (American Wire Gauge type 5 × 5 × 44/40) with an inductance of 185 µH. To assemble the antenna, we first cut three 18-m sections of wire. Each wire was separated by a minimum of 6.5 mm by using three 6.5-mm-diameter foam backer rods glued together to form a triangle (Fig. 1). Antenna wires were placed in the indentations between backer rods, creating a triangular wire gallery. Cellophane was then wrapped around the wire gallery to maintain wire position.

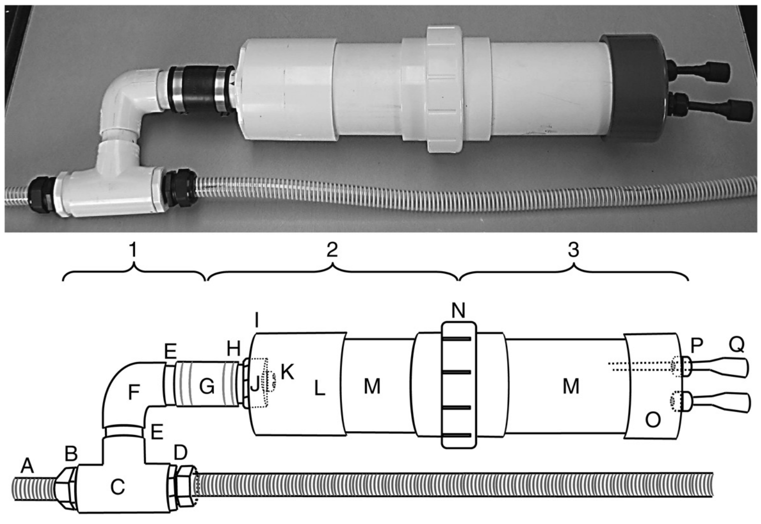
Once wrapped, the wire gallery was threaded through a 1.9-cm-diameter, flexible PVC hose, which formed the antenna housing. Each end of the hose was then inserted into the reader enclosure (described later), where the turns were soldered together. Two 8200-pF capacitors were soldered in parallel to one of the terminal wires. Finally, both terminal ends of the windings of antenna wires were connected to the reader, along with bus cables for the power and communication of the controller area network (CAN). The enclosure was sealed for deployment, and waterproof connectors and CAN-bus cable were used to connect the reader to another IS1001 antenna in series or to the IS1001 Master Controller.

IS1001 reader enclosure

Underwater deployment required the design and fabrication of a watertight enclosure to house the IS1001 reader near the antenna wires. We designed an enclosure to be hydrodynamically stable and durable in a variety of deployment strategies. The enclosure was constructed in 3 sections for ease of assembly and to allow access to the reader (Fig. 2). Primary components of the enclosure were schedule-40 PVC, with the exception of the schedule-80 PVC end cap, which was drilled and tapped for 2 nylon, submersible, single-cord grips (P/N 69915K53, McMaster-Carr Supply Co., Elmhurst, IL). Wet-pluggable connectors (P/N MCIL-8-FS MP, Teledyne Technologies Inc.,

[2] Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

[3] Biomark Inc. 2020. IS1001 reader standalone operation. User manual, rev. 11, 62 p. [Available from website.]



A 1.9-cm flex hose	G 5.1-cm rubber coupler	M 10.2-cm pipe
B 2.5-cm cable gland	H 5.1-by-3.8-cm reducer bushing	N 10.2-cm union
C 3.8-cm tee	I 10.2-by-5.1-cm reducer bushing	O 10.2-cm end cap
D 3.8-by-2.5-cm reducer bushing	J 3.8-by-1.3-cm reducer bushing	P 1.3-cm nylon single-cord grip
E 3.8-cm pipe	K 1.3-cm nylon double-cord grip	Q Waterproof connector
F 3.8-cm elbow	L 10.2-cm coupler	

Figure 2

Photograph and schematic of the enclosure used to house the IS1001 reader, capacitors, and terminal ends of the antenna wires. Components are schedule-40 PVC, except the end cap (O), which was schedule-80 PVC, and cord grips (B, K, and P). Sections 1–3 indicate the 3 removable sections of the capsule, with access points at a coupler (G) and union (N). Waterproof connectors (Q) provide power to the antenna reader and enable multiplexing and communication between antennas and the IS1001 Master Controller through the bus cable for the controller area network. This configuration was used in the antennas deployed for testing of their detection efficiency as part of a system to track migrating steelhead (*Oncorhynchus mykiss*) in Abernathy Creek, of Washington, in 2015.

Thousand Oaks, CA) were threaded through these cord grips and used to connect IS1001 readers and antennas to each other and to the IS1001 Master Controller. All power and communication to and from the reader and master controller traveled through CAN-bus cable.

The previously soldered antenna wire ends entered the lower section of the enclosure through nylon submersible cord grips (P/N 69915K71, McMaster-Carr Supply Co.) threaded into 2 sides of a PVC tee (Fig. 2, section 1). The tee covered these connections and allowed the 2 ends of the antenna loop to be threaded up through the top of the tee and into the main compartment of the enclosure, where it was connected to the reader (Fig. 2, section 2).

An internal multi-cord grip (P/N 7807K33, McMaster-Carr Supply Co.) was used to seal the entry point of antenna wires into the enclosure. This cord grip safeguarded against water intrusion and ensured compartmentalization in case of a water breach, minimizing potential damage to the reader. The second half of the main compartment allowed CAN-bus cables to enter the enclosure and connect to the reader (Fig. 2, section 3).

Once the antenna was constructed, frames of high tensile strength, made with rope of a small diameter that does not stretch, were used in all applications to relieve strain on antennas during deployment. The antenna was secured to the rope frame with cable ties placed at 0.3-m intervals, and plastic thimbles were spliced into the corners of the rope frame to connect multiple antennas to each other or to deployment structures.

Efficiency testing

Antenna efficiency was tested by deploying 3 flexible antennas (2.4 by 6.1 m) in Abernathy Creek, in Washington, prior to a release of hatchery-raised steelhead (*Oncorhynchus mykiss*) on 14 April 2015. Juvenile steelhead were reared and tagged with standard 12-mm PIT tags at the Abernathy Fish Technology Center, a hatchery of the U.S. Fish and Wildlife Service located 5 km from the mouth of the creek. All antennas were deployed in a single pool about 400 m downstream from the hatchery release site, where water velocity was approximately 0.6 m/s throughout.

One antenna was placed at the head of the pool and spanned the entire stream width (array 1). Two flexible antennas were required to span the pool at a second detection site (array 2), which was located 10 m downstream from array 1 and at the maximum water depth of the pool (1.8 m). None of the antennas were fully submerged for this test. Antennas were installed in a pass-through orientation by tying the top and bottom corners to trees and by using weights tied to short lanyards to anchor the bottom of the antennas to the stream bed. We used a Power Puller with a capacity of 2 metric tons (P/N 5541, Tekton Inc., Grand Rapids, MI) to increase tension on the top corners. Arrays were deployed for 45 h post release. In situ antenna efficiency and *combined efficiency* were then calculated as described by Zydlewski et al., (2006):

$$\text{In situ array 1: } E = (d_{\text{common to arrays }1+2}) \times (d_{\text{unique to array }2} + d_{\text{common to arrays }1+2})^{-1};$$

In situ array 2: $E = (d_{\text{common to arrays 1+2}}) \times (d_{\text{unique to array 1}} + d_{\text{common to arrays 1 + 2}})^{-1}$; and
Combined: $E = 1 - [(1 - E_{\text{in situ array 1}}) \times (1 - E_{\text{in situ Array 2}})]$,

where E = efficiency, and
d = the number of tags decoded.

Results

A total of 300 steelhead implanted with PIT tags were released from Abernathy Fish Technology Center on 14 April 2015. Of these steelhead, 265 fish were detected with antennas located at the hatchery exit, and 85 fish were detected with the 3 flexible antennas deployed downstream. Our upstream antenna (array 1) detected 57 fish, and the 2 downstream antennas (array 2) detected 52 of those 57 fish over the 45-h test period, giving array 2 an efficiency of 91%. Array 2 detected 75 fish, and 52 of those 75 fish were previously detected on array 1, giving array 1 an efficiency of 69%. The combined efficiency of both arrays was 97%. Of the 265 fish detected on antennas at the hatchery exit, 187 fish were later detected at the creek mouth on an array operated by the U.S. Fish and Wildlife Service. The median travel time, from the hatchery exit to the mouth of the creek, of these fish was 21.2 d, and their median travel speed was 0.24 km/d.

Discussion

Our flexible antenna has become a versatile tool used to detect PIT-tagged fish in traditional instream environments. Its adaptability makes it useful in both traditional and innovative approaches to PIT interrogation, such as those in which antennas have been attached to pile dikes (Magie et al.[4]) and towed behind 2 vessels (Morris et al.[5]). In arriving at a final shape and size of a rectangular antenna with dimensions of 2.4 by 6.1 m, we tested different shapes—including circles, squares, trapezoids, and rectangles—and sizes up to 3.0 by 18.3 m. All testing was done in air at our sample station near Jones Beach, Oregon.

The results of testing with circles indicate that a circle is the least efficient shape. Circular antennas quickly lost current and, therefore, detection area as their diameter increased. Results for squares were similar as their length and width increased. The results of testing with rectangles indicate that a rectangle is the most efficient shape, with a narrow width helping to maintain the antenna field and a strong detection area even as their length increased. At some point, the length of rectangles became too great, and the detection area started to weaken. Trapezoids worked as long as the reader could continue to tune the antenna. However, again, a trapezoid was not the most efficient design, and results for this shape compare more closely to those from testing with circles. The shape and size of antenna at which we arrived, on the basis of our testing, produced a substantial detection area, much greater than that of the standard rigid antennas that have been used in the past, and the electronic field was strong enough to handle the depletion of antenna current when deployed in water. It also allowed the antenna to transform in shape by about 1 m in any direction and maintain its functionality.

In creating such a large antenna, our 2 biggest concerns were higher susceptibility to electromagnetic interference and frequency of tag-code collisions due to large numbers of tagged fish entering the antenna field at the same time. As testing progressed, we found that electromagnetic interference was not a deterrent for any of our installations, but given the individual array efficiencies, tag collision was likely present.

Array efficiencies of 69% and 91% at Abernathy Creek indicate that tag collisions might have occurred during periods of high tag density. It is also possible that poor tag orientation contributed to missed detections as the fish moved through the detection field. These are the likely explanations for the lower efficiency of array 1 compared with that of array 2. Array 1 was a single antenna, whereas array 2 was composed of 2 antennas and therefore had more area for fish to pass through without causing tag collisions. River width and associated flow dynamics also may have contributed to suboptimal tag orientation as fish approached array 1. Further, our efficiency estimates may have been biased low, given the long travel times of fish exiting Abernathy Creek. It is also possible that 4 of the 5 fish detected on array 1 and missed on array 2 passed the first antenna and remained at the head of the pool, never reaching the second array during the test period. Of these 4 missed fish, 3 steelhead had travel times to the mouth of the creek that were well above the release group median (27, 28, and 35 d), and 2 fish were detected on the morning of system removal. Regardless of these unknowns, our estimated efficiency is comparable to that estimated for other PIT antennas that detect fish migrating downstream (Aymes and Rives, 2009; Zydlewski et al., 2006). Additionally, the combined array efficiency of 97% indicates the importance of redundancy for instream installations.

The results of the efficiency test also indicate the versatility of the antenna in a traditional instream application. Installing the system took only 3 h, and the weights used to maintain antenna orientation on the substrate remained stable during testing. Although this deployment was for only 2 d, the ability of the flexible antenna to conform to the streambed, as well as its relatively small diameter,

[4] Magie, R. J., M. S. Morris, J. P. Bender, B. F. Jonasson, B. P. Sandford, and R. D. Ledgerwood. 2015. Development of a passive integrated transponder (PIT) tag detection system for adult salmonids in the lower Columbia River, 2013, 33 p. Fish Ecol. Div., Northwest Fish. Sci. Cent., Natl. Mar. Fish. Serv., Seattle, WA. [Available at website.]

[5] Morris, M. S., A. J. Borsky, P. J. Bentley, L. N. Webb, and B. P. Sandford. 2017. Detection of PIT-tagged juvenile salmonids migrating in the Columbia River estuary, 2016, 45 p. Contract report to the Bonneville Power Administration, U.S. Department of Energy (contract no. 46273 RL58; project no. 1993-029-00). Fish Ecol. Div., Northwest Fish. Sci. Cent., Natl. Mar. Fish. Serv., Seattle, WA. [Available at website.]

resulted in less drag and buoyancy in the water than we have observed in similar stream deployments of rigid antennas. Although the flexible antenna was less likely to become disoriented in strong currents, larger weights and more permanent anchors should be used for long-term installations and at sites where water levels and velocities change throughout the year. Pass-over configurations in which flexible antennas are used are also a feasible option.

We tested various components and materials to address the challenges associated with rigid antennas, mainly bulk, weight, reduced mobility, and cost. The resulting antenna design covered a large detection area, and its lightweight construction and flexibility increased utility. Elements of this design are now available commercially, in part because the antenna is adaptable to a wide range of geographic locations, environmental conditions, and freshwater habitats. Installations of flexible antenna arrays for detection of PIT-tagged fish offer considerable potential to advance our understanding of stock-specific differences in behavior, migration timing, and survival, as well as to improve evaluations of restoration and recovery efforts for threatened and endangered species.

Resumen

Se ha desarrollado un novedoso diseño de antena para detectar peces implantados con etiquetas “full duplex” de transmisor pasivo integrado (PIT). La antena está fabricada con manguera flexible ligera y mide 2.4 por 6.1 m, lo que proporciona un alcance de lectura sustancialmente mayor que el de otras antenas PIT. En este artículo se describe su uso en un pequeño sistema de monitoreo para detectar la migración de la trucha arcoiris (*Oncorhynchus mykiss*). Durante las pruebas, la eficacia de detección combinada de los dos conjuntos de antenas con el nuevo diseño fue del 97%, comparable a las antenas estándar fabricadas con cloruro de polivinilo o polietileno de alta densidad. El diseño ligero y flexible de la nueva antena permite transportarla y desplegarla con relativa facilidad en comparación con las antenas rígidas, y para su mantenimiento y despliegue se necesitan tripulaciones y embarcaciones más reducidas. El desarrollo de la antena flexible ha ampliado la utilidad de la tecnología PIT al aumentar el alcance de las posibles aplicaciones de muestreo a una gama más amplia de hábitats y condiciones ambientales.

Acknowledgments

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