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A Monolithic Multi-Channel Amplifier for Electrode Arrays

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***Abstract*—We present a monolithic microelectronic multi-channel amplifier designed to facilitate measurements from multi-electrode arrays. A single silicon chip includes sixteen electrode amplifiers, along with interface and control circuitry to allow data collection through a compact 4-wire interface.**

I. Introduction

Bioelectric instruments of all kinds must address the basic problem of maintaining signal integrity between the distal and proximal portions of the instrument. The distal portion of the instrument is embedded in some biological tissue, and is typically an array of electrodes. The proximal portion of the instrument is some kind of control and data-logging engine operated by the experimenter. The fundamental purpose of the instrument is generally to transfer signals between the two portions of the apparatus, whether to deliver signals to the electrodes for stimulation, or to record signals from the electrodes, or both.

Electromagnetic interference ("EMI") and noise present ubiquitous threats to signal integrity. The communication channel between distal and proximal instrument segments is a primary point of vulnerability for EMI and noise. This channel may be physically realized as a collection of electrical conductors (a "cable"), an optical fiber, or some kind of wireless communication link.

The desire for EMI resistance drives us to locate active electronic circuitry in the distal portions of the instrument, close to the electrodes. This physical proximity between electrode and electronics reduces unintended antenna effects in the connecting wires. The function of the distal electronics is to behave as a suitable interface between the electrodes and the communication channel.

In order to prevent the bioelectric instrument from unduly interfering with the biological tissue of interest (and perhaps interfering with the entire organism), an experimenter typically prefers to make the distal portions of the instrument as small and lightweight as possible, dissipate as little electrical power as possible, and require as little cable size, mass, and stiffness as possible. As the number of electrodes in an array is increased, these technological problems become more significant barriers in the construction of the apparatus [1, 2].

Reduction of size, weight, and power (SWAP) is also a major driving force in the technology development of commercial consumer electronics. Consumer electronic devices typically achieve SWAP reduction by integrating many electronic functions onto a single integrated circuit chip.

We present a silicon microelectronic device designed to fit gracefully into the distal portions of multi-channel bioelectric instrumentation. The device presented is a multi-channel amplifier ("MUXamp"), with time-division multiple-access (TDMA) readout through a compact 4-wire interface. The MUXamp device is presented as a functioning illustrative example of a wide class of devices which can enable facile construction of multiple electrode arrays for bioelectric instruments, including recording, stimulation, or both functions.

II. Description of the MUXamp Device

The MUXamp is a single silicon chip, 2.25mm X 1.75mm in size, comprising 16 low-noise amplifiers and associated control circuitry. The MUXamp chip is programmed from a NeuroTalk2 (NT2) serial data interface, and requires only 4 wire connections to the data collection equipment. The NT2 bus is a compacted variant of the NeuroTalk ASIC interface [3]. Each MUXamp chip is individually addressable over the command line of the NT2 interface. Multiple chips (and therefore multiple electrode arrays) can share a common bus. Presently, 16 MUXamp chips may share a single 4-wire NT2 bus — up to 256 electrodes may be connected through a single 4-wire bus, from the standpoint of communication and control.

A. Logical architecture of the MUXamp

1) general description

Fig. 1 illustrates the overall logical structure of the MUXamp device.

Each electrode input channel (CH0 – CH15) on a MUXamp chip is AC-coupled, with all signals referred to a common reference voltage level buffered from an additional electrode input (REF). The amplifier outputs are available through a programmable analog switch matrix. Internal logic controls the switches to deliver a TDMA analog stream which includes a frame marker sequence and a programmable number of time slots in each frame.

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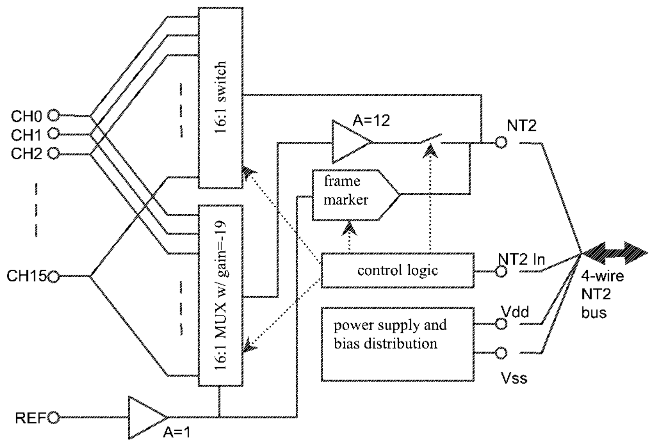

Fig. 1: Block diagram illustrating the logical structure of the MUXamp device.

2) *operating modes of the MUXamp*

. The MUXamp device has two modes of function:

a. direct connection, in which a channel input terminal is directly switched to the NT2Out.

b. amplified connection, in which the voltage at the channel input terminal is amplified though an AC-coupled gain pathway with a total inverting voltage gain of about 250, before connection to the NT2Out terminal.

a) Direct connection

If any of the channels is "direct" connected, the amplifier chain is disabled, to prevent the amplifier output from driving any of the input terminals through the direct-connect switch. Any of the channels may be direct-connected to the MUXamp output terminal. If more than one channel is direct-connected at one time, then the voltage at one direct-connected input will influence the voltage at all other direct-connected inputs, through the direct-connect switches. Direct-connect switch impedance is nominally 200 ohms. The direct-connection mode would be used for diagnostics of the electrodes, for example when desiring to measure the electrode impedance.

b) Amplified connection

If none of the channels is direct-connected, the amplified MUX function is allowed to operate, driving the NT2Out terminal with a gain-of-250 sample stream of the selected channels. None, any, or all of the channels may be selected for inclusion in the MUX sample stream. The amplified MUX stream is formatted as a variable-length frame, with the various data channels occupying ordered time slots within each frame. The total length of a frame is determined by the number of channels chosen for inclusion. Included channels are sampled in ascending numerical order within a frame. The slot pointer is advanced on the rising edge of the system clock. The time slot structure of a sample frame is illustrated in Fig. 4.

3) *signal processing pathway*

Fig. 2 details the signal pathway between an electrode connection terminal and the NT2 Out bus connection. The aggregate gain from the electrode to the NT2 bus connection is approximately -240 V/V, with most of the voltage gain delivered by a low-noise amplifier connected to the electrode.

Signals from the electrode are AC-coupled into the front-end amplifier through a 13pF capacitor, and the DC baseline is restored to a common reference level. In order to capture a bandwidth of interest for bioelectric measurements, the AC-coupling highpass frequency is set to approximately 0.2Hz.

An internal MUX bus joins all 16 MUX switches on the 16 front-end amplifiers to a common output buffer. The detail of Fig. 2 shows that the output buffer is composed of two switched-capacitor gain stages, which are reset during the frame-marker portion of each TDMA frame.

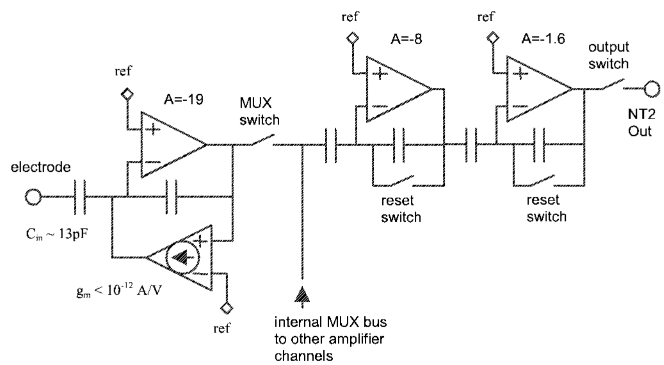

Fig. 2: The signal processing pathway through the MUXamp device begins with a low-noise AC-coupled gain stage prior to signal steering circuitry and additional gain.

The voltage gain of each channel is set by the ratio of two capacitors integrated on the MUXamp chip. Note that while the absolute capacitance values of capacitors on a CMOS chip may be relatively inaccurate (up to 20 percent value variation compared to the design target value), the ratio of capacitance between two capacitors on the same chip can be held to very tight tolerances, typically in the range of 0.1 percent. Hence, the voltage gains of the MUXamp channels are very closely matched.

The front-end circuit is AC coupled, with a highpass corner frequency of roughly 0.2Hz. Because the capacitance of the input circuit is on the order of 10pF, the feedback resistance required for the highpass corner is on the order of 10^{13} ohms. Such large resistances are not practical to build in ordinary silicon CMOS fabrication processes, so we designed a transconductance circuit to accomplish the low-frequency feedback.

Each front-end amplifier is connected to a common reference voltage level. The reference voltage is buffered from an external connection to the MUXamp chip. The REF connection to the MUXamp chip presents a high impedance to external circuitry, and may be connected to a reference electrode, or to some other suitable reference voltage

4) control logic

Control logic on the MUXamp chip allows an NT2 input stream to control operation of the chip. The NT2 data stream for the MUXamp device is composed of a 4-bit device address, a 4-bit operation code (“opcode”), and a 16-bit data payload to be delivered to the specified device.

The MUXamp control logic deciphers the unit address and opcode, from the incoming NT2 data stream, and adjusts internal switch settings if appropriate. Another function of the control logic is to generate a channel commutation clock from the NT2 stream, and cycle through the chosen amplified channels. Sample timing is determined by the clock derived from the externally-supplied NT2 data stream. Sample clock latency is less than 100ns from an incoming NT2 edge to a channel change.

Figure 4 shows a measured example of a TDMA frame from a MUXamp chip running at a frame rate of 820Hz, sampling all of its 16 available channels. Each TDMA frame is composed of a frame marker sequence followed by a set of samples from the chosen channels. The frame marker sequence is a series of four time slots, occupied by: MIN, MAX, RECOVER, and REF. The MIN and MAX levels are the minimum and maximum extrema of the chip’s power supply, and these voltage levels represent the absolute limits of any possible amplifier output excursions. The REF level is a sample of the common reference voltage, to which all of the channel samples are referred (that is, if all of the channel inputs were at fixed DC levels, the AC coupling would eventually drive the output samples to the REF level). The RECOVER time slot is included in the frame marker sequence to allow time for the output buffer amplifier to recover from the large voltage excursions imposed by the MIN and MAX levels. The frame marker sequence serves two important purposes:

1. The REF sample allows re-calibration of the voltage datum for the channel samples. Any common drift in the electrode array voltage levels (with respect to the external data collection machinery) is nulled by the inclusion of the voltage reference sample in each frame; this arrangement amounts to a pseudo-differential measurement.

2. The MIN-MAX couplet is a readily identifiable event in the TDMA stream, enabling the necessary alignment of time slots so that the various channels in the TDMA stream may be correctly logged by the external data collection engine.

During the period in which the internal switches connect a particular channel to the NT2 output terminal, the full 400kHz bandwidth of the signal processing pathway is available. This non-sampling structure allows high-bandwidth examination of selected channels. Figure 5 shows a captured oscilloscope trace of a fragment of an NT2 frame in which one of the channels is connected to a high-frequency sinewave source, while the adjacent channels are connected to DC levels. The clock transients are clearly visible in the NT2Out signal trace

B. Physical architecture of the MUXamp

Fig. 3 shows a labeled CAD layout of the MUXamp chip. The chip is quite small, designed to fit onto a commercially available electrode array (MicroProbe FMA series). Nonetheless, the chip layout has considerable “white space,” and can accommodate improvements or additions.

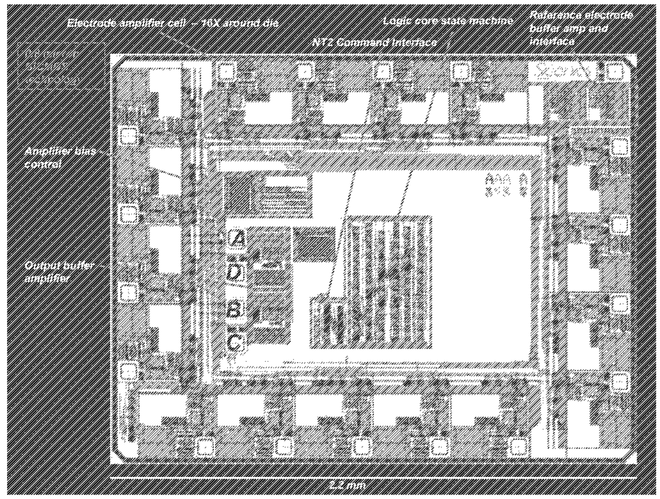

Fig. 3: Labeled CAD layout of the V1.0 MUXamp chip. The chip, sized to fit onto a commercially available electrode array, clearly has space for additions and improvements.

III. MUXAMP PERFORMANCE

Dry bench-testing of the V1.0 MUXamp devices shows encouraging performance figures, adequate for many bioelectric measurement applications. Table 2 details the measured performance of the device.

TABLE 2.
MEASURED PERFORMANCE OF THE MUXAMP V1.0

description	**value**
size	2.25mm X 1.75mm
mass	< 10 milligrams (bare die)
power dissipation	10mW at 3.3V
input-referred noise	18μVrms, 10Hz to 10kHz
input impedance	13pF ‖ R_{in} ($R_{in} > 10^{11}$ ohms)
output impedance	2100 ohms
voltage gain	-250 V/V
max load capacitance	∞ (unconditionally stable)
highpass corner frequency	0.2 Hz
gain path bandwidth	400 kHz ($C_{load} < 50pF$)

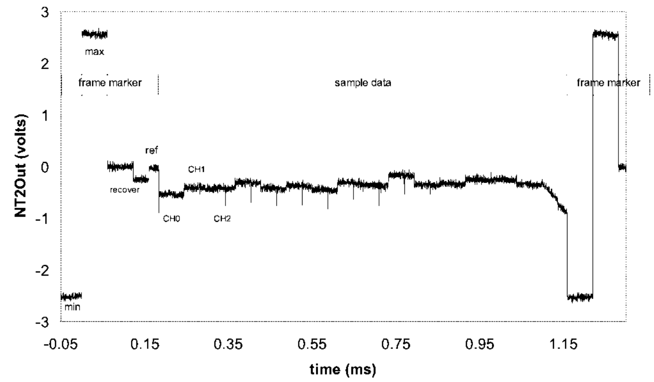

Fig. 4: A measured example of a full 16-channel sample frame from a MUXamp chip running at a rate of 820 sample frames per second.

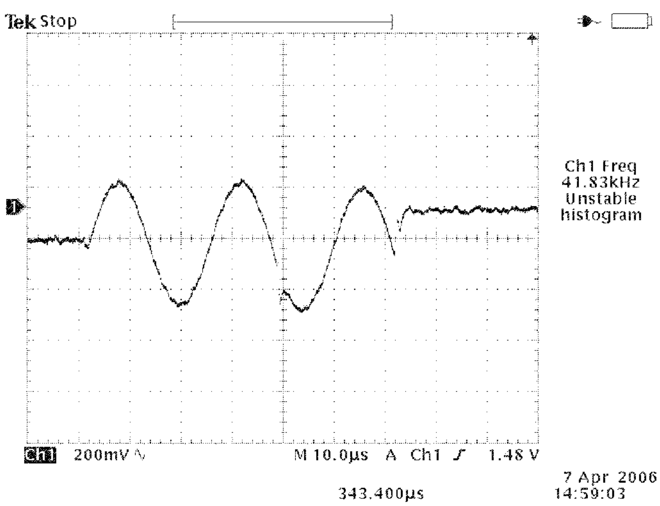

Fig. 5: A captured oscilloscope trace of the NT2Out signal as the MUX switches across three channels, two connected to DC levels and one with a 42kHz sine source.

IV. Looking Forward

Existing data logging systems are not readily capable of recovering separated channel data from the TDMA stream produced by the MUXamp device. Therefore, we intend to design and build an analog data decommutator device ("deMUX"), similar to the simplified block diagram of Fig. 5. The deMUX device will be a low-power monolithic integrated circuit device, designed to be a matched companion to the MUXamp device.

The deMUX will include an NT2 data interface, a frame-boundary discriminator, and a set of analog sampling buffers with their associated control and support circuitry. Each sampling buffer will be programmed to take samples at appropriate instants to recover the samples from a single MUXamp channel. The deMUX device will share the NT2 bus with the MUXamp. Each deMUX chip will have a device address, and will be set up by the same data stream used to configure the MUXamp with a corresponding address.

In order to correctly unravel the analog TDMA stream from the MUXamp, the deMUX device must achieve four critical timing tasks:

1. Align the sample-and-hold timing correctly with respect to the frame boundary
2. Assign each sample to its appropriate output channel
3. Align the precise sampling time correctly within the time slots
4. Properly set the lowpass filter frequency for good anti-alias performance

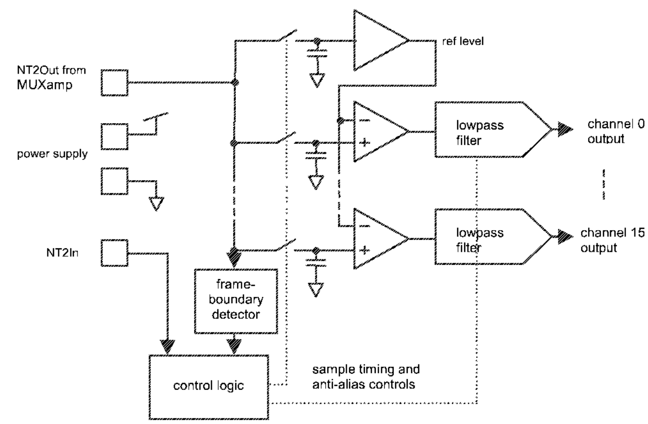

Fig. 5: Block diagram of a "deMUX" companion device for extracting separated analog channel data streams from the MUXamp TDMA stream.

Because of the flexibility of the general architecture of the NT2 bus, we can envision a wide variety of building-block components in addition to the MUXamp presented in this paper. A bioelectric instrument might make use of distal electronics which incorporate stimulation devices, recording amplifiers, and mixed-function devices, all connected to the proximal control console by an NT2 communication bus.

V. References

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