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Combining Techniques in MIMO Communication Systems

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ABSTRACT: In MIMO communication systems, appropriate combining techniques must be applied to minimize the inter-symbol interferences (ISI) to ensure an accurate decoding of transmitted symbols. In this paper, four combining techniques are illustrated, compared, and simulated in terms of the bit-error-rate (BER) versus signal-to-noise ratio (SNR): zero-forcing combining (ZF); V-BLAST combining, linear minimum mean square combining (LMMSE) and maximum likelihood (ML) combining. The discussion of performances and execution time in rich scattering MIMO channel is also included. Simulation results in MATLAB indicate that ML combining yields the smallest BER whereas also consumes the most execution time. V-BLAST, LMMSE combining are in general better than ZF combining with similar computation complexity.

KEYWORDS:MIMO, combining techniques, zero-forcing, linear minimum mean square combining, maximum likelihood.

I.INTRODUCTION

Multipath wireless channel has been demonstrated to be capable of enormous communication capacities [1-3]. Specifically, multiple-input and multiple-output, or MIMO communication systems utilize multiple transmission and receiving antennas to exploit multipath propagation and to combat channel fading [4-6]. As illustrated in Fig. 1, the spectral diversity is achieved by multiple TX antennas and RX antennas, each operating simultaneously and within the same frequency range. The RX antennas can be viewed as multiple users distributed in the coverage area. By paralysing the data streams and sending them from different antennas, the data streams will go through different channel paths, i.e., h_{11},h_{21}, and the RX antennas will receive information from different TX antennas as well as different paths. In fast fading channels, each TX antenna sends the same data stream to combat channel fading since each reception is independent. In flat fading channels, however, each antenna could send different data streams to increase the system throughput. However, inter-symbol interference (ISI) will appear since RX_1 will not only receive data from TX_1, but also TX_2, etc.

Consequently, appropriate combining techniques have been investigated to ensure a successful decoding of transmitted data streams. Specifically, this paper illustrates the algorithms for four commonly used combining techniques: zero-forcing combining (ZF) [8]; V-BLAST combining [7], linear minimum mean square combining (LMMSE) [11] and maximum likelihood (ML) combining [9][10]. The MIMO channel model assumptions are illustrated in Section II. Specifically, 4*4 channel and 8*8 rich scattering channels are tested. Section III contains the detailed algorithms of the four combining techniques. The simulation results of bit-error-rate (BER) versus signal-to-noise (SNR) ratio and the execution time are included in Section IV. The simulations are performed in MATLAB and the SNR ranges from -20 dB all the way to 20 dB. Finally, the discussion on the performances and execution time is included in Section V. Section VI concludes the paper.

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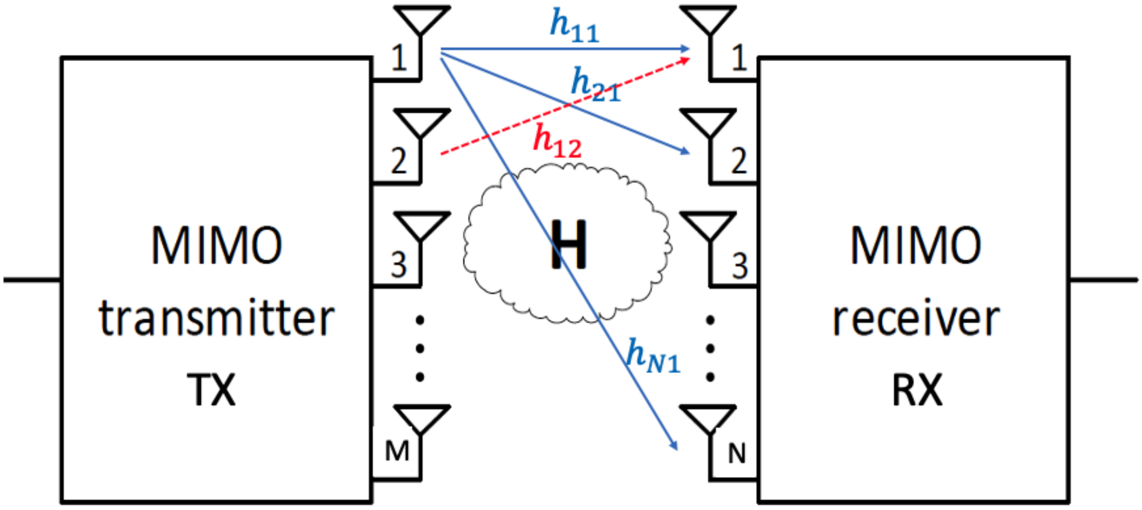

Fig. 1 MIMO channel model with M transmit antennas and N receiving antennas

II.MIMO CHANNEL MODEL AND ASSUMPTIONS

The MIMO system considered in this project consists of M transmit antennas and N receive antennas. The transmitted symbols are:

$$\vec{a} = \begin{Bmatrix} a_1 \\ a_2 \\ \cdots \\ \cdots \\ a_M \end{Bmatrix}$$

, where each transmitter is supposed to use the same modulation scheme. Specifically, BPSK and QPSK modulation is considered during implementation.

The channel is supposed to be rich-scattering channel, with the channel matrix given by:

$$H_{N\times M} = \begin{Bmatrix} h_{11} & \cdots\cdots & h_{1M} \\ h_{21} & \cdots\cdots & h_{2M} \\ \cdots & \cdots\cdots & \cdots \\ h_{N1} & \cdots\cdots & h_{NM} \end{Bmatrix}$$

, where h_{ij} is the complex transfer function from transmitter j to receiver i, as shown in Fig.1.

In paper [7], the channel matrix is got from training sequences. In simulation, the channel coefficient h_{ij} is supposed to be Gaussian random variable with zero mean and unit variance. Either case, the receiver is assumed to have full knowledge of channel matrix for decoding.

In MIMO systems, the receivers operate co-channel, each receiving the signals radiated from all M TX antennas. Hence, there will be interferences among symbols (transmit streams) and different combining techniques can be applied to decode the transmit symbols.

Specifically, four types of combining techniques are considered in this paper: zero-forcing combining (ZF); V-BLAST combining, linear minimum mean square combining (LMMSE) and maximum likelihood (ML) combining.

III.MIMO COMBINING TECHNIQUES

In this section, the algorithms for the four combining techniques are introduced.

The received symbols after the MIMO channel are given by:

$$r_{N\times 1} = H_{N\times M} a_{M\times 1} + n_{N\times 1}$$

, where a is the transmitted vector and n is noise vector.

The purpose of combining is to counteract the effects of channel matrix $H_{N\times M}$ and recover $a_{M\times 1}$ from $r_{N\times 1}$ underdifferent SNR values.

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(1) Zero-forcing combining (ZF)

The key step in ZF combining is to find the weighting vector w_i^T such that $w_i^T H(:,j) = \delta_{ij}$.
And such weighting vector can be found by taking the pseudo inverse of the channel matrix:

$$G_{ZF} = (H^H H)^{-1} H^H$$

and w_i^H is the i-th row of G_{ZF}.
When H is a square matrix, which means $N = M$, then $G_{ZF} = H^{-1}$.
Then the decision statistics for ith sub-stream is:

$$y_i = w_i^T r = w_i^T (Ha + n)$$

Afterwards, the decision statistics is quantized to get the transmitted symbol:

$$\hat{a}_i = Q(y_i)$$

The quantization depends on the modulation technique. For example, if BPSK modulation is used, then if real(y_i)>0, the quantized symbol is +1. If real(y_i)<0, the quantized symbol is -1.

For QPSK modulation, the following table summarized the four possibilities:

$\hat{a}_i$	real(y_i)>0	real(y_i)<0
imag(y_i)>0	$\frac{1}{\sqrt{2}} + j\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}} + j\frac{1}{\sqrt{2}}$
imag(y_i)<0	$\frac{1}{\sqrt{2}} - j\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}} - j\frac{1}{\sqrt{2}}$

Finally, the quantized symbols are mapped to the transmitted bits.

(2) V-BLAST combining

The V-BLAST combining can be viewed as an extension of ZF in two aspects.
Firstly, the symbols are not detected using the weighting vector from a single G_{ZF}, but are decoded one-by-one. The detection order matters in the sense to maximize the post-detection SNR.
Secondly, the detected symbols are subtracted from the received signal $r_{N\times 1}$ to reduce the inter-symbol interferences. In this sense, the V-BLAST combining is supposed to have lower BER under the same channel noise (or transmit SNR value).
The algorithm for V-BLAST combining is summarized below.

Set the detection order

$$S = \{k_1, k_2, \ldots, k_M\} \quad (2\text{-}1)$$

Initialization:

$$i = 1 \quad (2\text{-}2)$$

$$G_1 = (H^H H)^{-1} H^H \quad (2\text{-}3)$$

$$k_1 = argmin\|(G_1)_j\|^2 \quad (2\text{-}4)$$

$$r_1 = Ha + n \quad (2\text{-}5)$$

Recursion:

$$fori = 1\ tolength(S) - 1 \quad (2\text{-}6)$$

$$w_{k_i}^T = G_i(k_i,:) \quad (2\text{-}7)$$

$$y_{k_i} = w_{k_i}^T r_i \quad (2\text{-}8)$$

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$$\widehat{a_{k_i}} = Q(y_{k_i}) \tag{2-9}$$

$$r_{i+1} = r_i - \widehat{a_{k_i}}.*H(:,k_i) \tag{2-10}$$

$$H = H\_(zeroing k_1 to k_i volumns) \tag{2-11}$$

$$G_{i+1} = (H^H H)^{-1} H^H \tag{2-12}$$

$$k_{i+1} = argmin\left\|(G_{i+1})_j\right\|^2 \tag{2-13}$$

End recursion

$$w_{k_{i+1}}^T = G_{i+1}(k_{i+1},:) \tag{2-14}$$

$$y_{k_{i+1}} = w_{k_{i+1}}^T r_{i+1} \tag{2-15}$$

$$\widehat{a_{k_{i+1}}} = Q(y_{k_{i+1}}) \tag{2-16}$$

The reason for selecting the order of detection by finding the row vector that has minimum norm, as indicated in (2-4) and (2-13) is that such order will give the highest post detection SNR, which is defined as:

$$SNR_{k_i} = \frac{\left|a_{k_i}\right|^2}{\sigma^2\left\|w_{k_i}\right\|^2}$$

, where a_{k_i} is the transmitted symbol, σ is the variance of noise, and the w_{k_i} is different every stage. Since a_{k_i} is supposed to have the same constellation, the component with the smallest SNR_{k_i} will dominate the SNR of the system. [7] suggests that simply choosing the best SNR_{k_i} at each stage in the detection process leads to the globally optimum ordering, S_{opt}.

The cancellation of the detected symbols is done through (2-10) to (2-11). A simple way of understanding why such cancellation will work is illustrated below:

Suppose N=M=2. Then the received signal vector is given by

$$\begin{pmatrix} r_{11} \\ r_{21} \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}$$

Suppose during the initialization stage, $k_1 = 1$, which means a_1 is detected first. Then, during the second round, the first column of H matrix is set to zero, which is equivalent to setting $a_1 = 0$. If noise is ignored, the received signals become

$$r_2 = \begin{pmatrix} r_{11}' \\ r_{21}' \end{pmatrix} = \begin{pmatrix} 0 & H_{12} \\ 0 & H_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \begin{pmatrix} 0 \\ a_2 \end{pmatrix} = \begin{pmatrix} H_{12}a_2 \\ H_{22}a_2 \end{pmatrix}$$

$$= \begin{pmatrix} r_{11} \\ r_{21} \end{pmatrix} - \begin{pmatrix} H_{11}a_1 \\ H_{11}a_1 \end{pmatrix}$$

According to (2-12), $G_2 = pinv\begin{pmatrix} 0 & H_{12} \\ 0 & H_{22} \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ G_{21} & G_{22} \end{pmatrix}$.

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And $y_{k_2} = w_{k_2}^T r_2 = (G_{21}, G_{22}) \binom{r_{11}'}{r_{21}'} = G_{21} r_{11}' + G_{22} r_{21}' = G_{21}(H_{12} a_2) + G_{21}(H_{22} a_2)$

$$= (G_{21} H_{12} + G_{22} H_{22}) a_2 = a_2 \text{ since } G_2 = pinv \begin{pmatrix} 0 & H_{12} \\ 0 & H_{22} \end{pmatrix}.$$

The above example validates that the V-BLAST technique is correct when there is no noise. When noise is present, V-BLAST will have better performance than ZF by virtue of the interferences cancelling.

(3) Linear Minimum Mean Square Combining (LMMSE)

The LMMSE is an extension of ZF combining in that it takes the SNR into account when deciding the weighting vectors. In other words,

$$G_{MMSE} = \left(H^H H + \frac{1}{SNR} I \right)^{-1} H^H$$

, and the weighting vector w_k^H is the k-th row of G_{MMSE}.

Then, similarly, the decision statistics for i^th sub-stream is:

$$y_i = w_i^T r = w_i^T (Ha + n)$$

Afterwards, the decision statistics is quantized to get the transmitted symbol:

$$\hat{a}_i = Q(y_i)$$

(4) Maximum Likelihood (ML) combining

The ML combining can be understood as a brute searching technique that considers all the possible symbol combinations. The vector x that gives the minimum norm between received signals and Hx is chosen. In this sense, ML will give the most accurate estimation since all the possibilities are considered.

$$\hat{x}(ML) = argmin\|y - Hx\|$$

The drawback of ML is that the computation time will grow exponentially as the number of TX or RX grows or the modulation level grows. The following table summarizes the required loop for ML:

4*4 BPSK	$2^4 = 16$
4*4 QPSK	$4^4 = 256$
8*8 BPSK	$2^8 = 256$
8*8 QPSK	$4^8 = 65536$

Table 1. Iteration numbers for ML combining under different MIMO channels

IV.SIMULATION RESULTS

4*4 and 8*8 MIMO channels with BPSK modulation and QPSK modulation are considered. The simulations are performed in MATLAB with the parameters summarized in Table 2.

4*4 BPSK	Iterations cycles=5000; SNR from -20dB to 20dB, step=1 dB
4*4 QPSK	
8*8 BPSK	
8*8 QPSK	Iterations cycles=2000; SNR from -20dB to 20dB, step=2 dB

Table 2. MATLAB simulation setups

From Fig.2 and Fig.3, the ML combining will give 0 BER after SNR=6dB for 4*4 channel and after SNR=3dB for 8*8 channel. Note that the SNR in the plots refers to the transmitted symbol power versus noise power. And it is also used to generate random Gaussian noise.

The codes execution time is summarized in Table 3.

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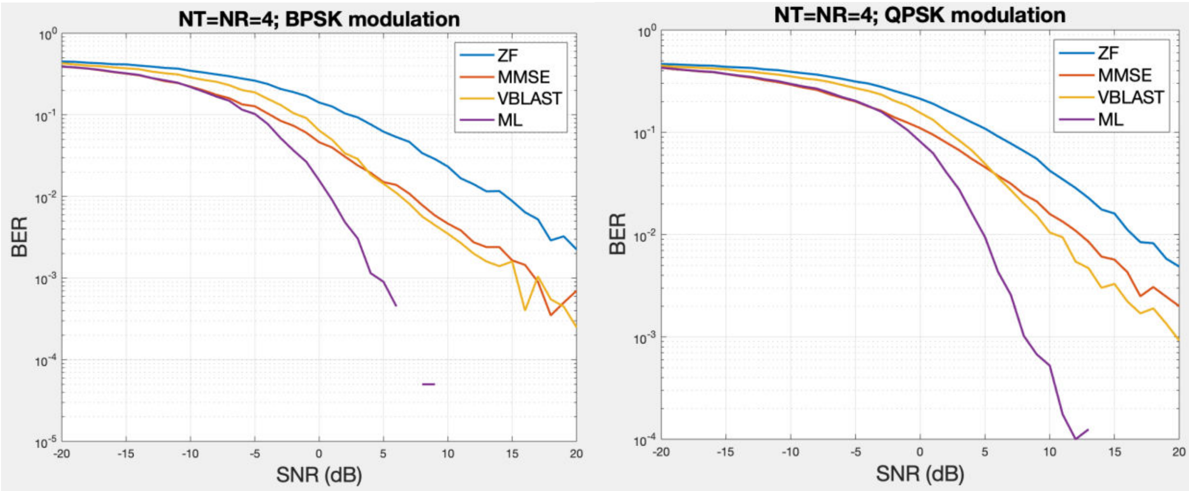

Fig. 2 Bit-error-rate (BER) versus signal-to-noise-ratio (SNR) for 4*4 BPSK modulation and QPSK modulation

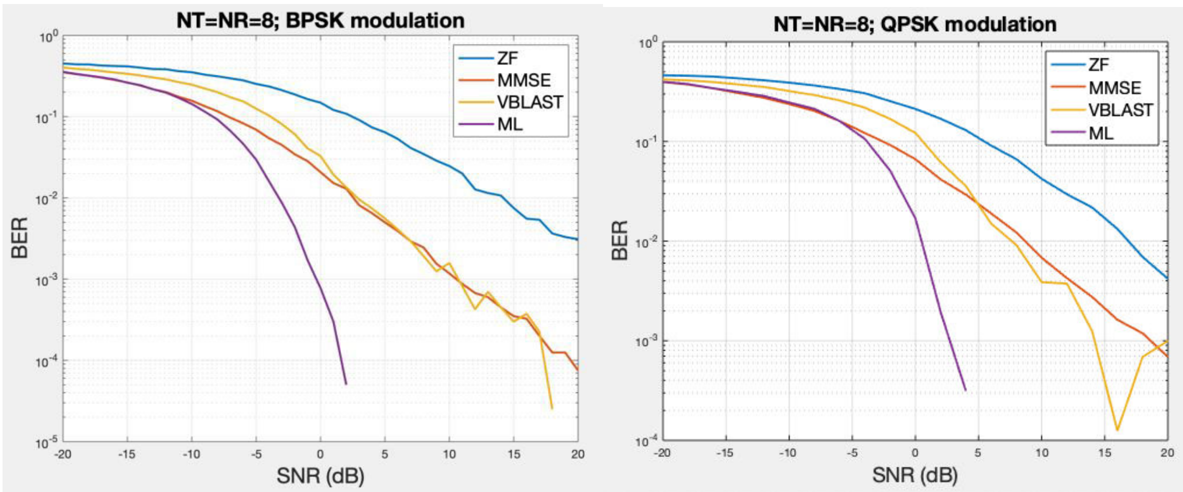

Fig. 3 Bit-error-rate (BER) versus signal-to-noise-ratio (SNR) for 8*8 BPSK modulation and QPSK modulation

	BPSK 4*4	QPSK 4*4	BPSK 8*8	QPSK 8*8
ZF	3.30s	3.13s	3.38s	3.25s
V-BLAST	4.67s	4.44s	5.83s	5.97s
LMMSE	5.52s	5.18s	5.55s	5.52s
ML	7.45s	14.65s	16.13s	564.84s

Table 3. Comparison of execution time for the four combining techniques. 1000 iterations are performed with 10 different SNR values.

V. DISCUSSION

In terms of performance, the ML has the smallest BER under the same SNR value. LMMSE and V-BLAST are not that good, but still perform better than ZF. As stated earlier, these two combining techniques could be considered as extensions of ZF combining. And the simulation results validate that the refinement to the weighting vectors do give better system performances.

In terms of execution time, the ML will take the longest time as expected. With number of antennas growing, the execution time will increase dramatically. ZF, V-BLAST and LMMSEare on the same order of execution time, which are not influenced by the number of antennas or the modulation levels.

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VI.CONCLUSION

In summary, this paper summarized four commonly used combining techniques in the MIMO communication systems. The detailed analysis of the algorithms is included, with the discussion about their theoretical performances. The simulation results from MATLAB validate the statements. This paper gives insights about how to choose the appropriate combining techniques in MIMO systems. For instance, when the accuracy is the top priority, ML combining should be used. If, however, the execution time is also a concern, V-BLAST and LMMSE combining can be adopted that give fair BER with moderate execution time.

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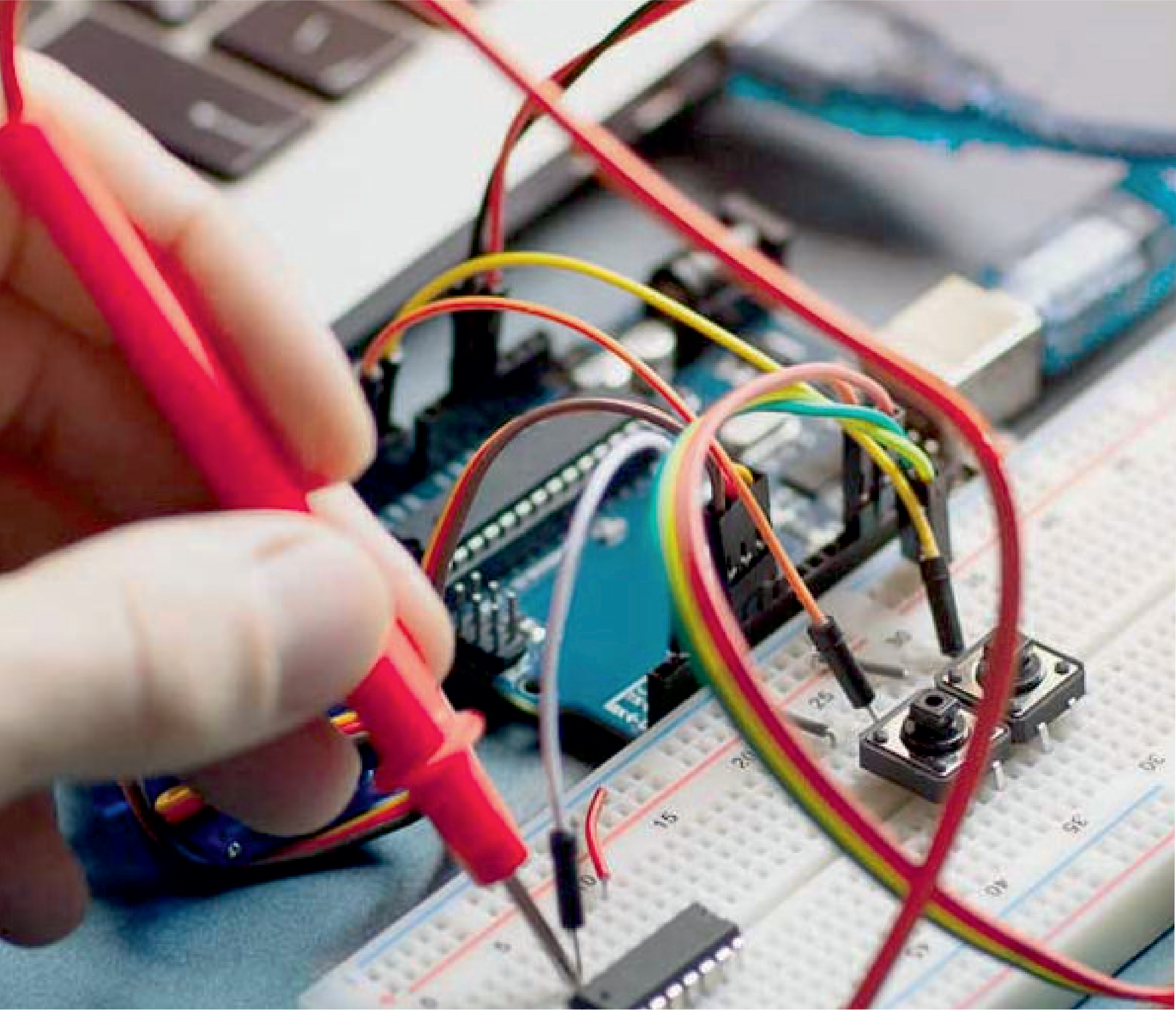

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