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Low Power Collision-Tolerant Media Access Control with On-Off Accumulative Transmission

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***Abstract*—In this paper, a cross-layer collision-tolerant (CT) media access control (MAC) scheme is proposed to achieve reliable low power communications for one-hop asynchronous wireless sensor networks (WSNs). Unlike conventional MAC schemes that discard and retransmit signals colliding at a receiver, the CT-MAC extracts the salient information from the colliding signals by leveraging on the signal processing capability in the physical layer with a new on-off accumulative transmission (OOAT) scheme. Nodes employing OOAT deliver information to a base station (BS) through asynchronous duty-cycled transmission (on-off transmission) of multiple identical sub-symbols (accumulative transmission). The on-off transmission reduces collision probability at the BS, and the accumulative transmission in the time-domain enables the simultaneous detection of colliding signals in the spatial-domain. An optimum maximum likelihood sequence estimation detector with *time-varying* trellis structure is employed by the BS to perform detection over the colliding signals.**

I. Introduction

Low power consumption is one of the most formidable challenges faced by the development of the next generation wireless sensor networks (WSNs) for applications such as structure health monitoring, environmental monitoring, and biomedical sensing [1] - [3]. To match the life cycle of the monitored objects, WSNs are often expected to operate uninterrupted over a long period of time under stringent energy constraints. Different from conventional communication system, many of the low power WSNs can operate with a very low data rate and a high tolerance to transmission latency due to the slow changing rate of the monitored objects. Such unique properties motivate the development of new communication techniques that are designed specifically for low power WSNs.

Existing low power communication schemes are developed in various forms at the physical layer and the media access control (MAC) layer [4] - [8]. Most physical layer low power communication techniques are developed by exploiting the tradeoff between power efficiency and spectral efficiency, such as modulation scaling [4], and on-off keying [5]. In the MAC layer, there are two categories of low power techniques. The first category, such as preamble sampling [6], and opportunistic aggregation [7], reduces power consumption by decreasing the sensor node duty cycle. The second category carefully coordinates the transmission of the sensor nodes to reduce collision at the receiver [8]. All are based on the conventional MAC approach, where signals colliding at a receiver will be discarded and retransmitted. This results in a waste of precious transmission power. In a low power WSN, we might not afford the luxury of discarding collided messages, which still contain salient information and can help signal detection. In addition, most of the low power schemes are developed by following the traditional layered-protocol design approach. While the layered design approach carries significant advantages for conventional communication networks, it cannot capture the interactions among protocol layers that might be critical to low power communications.

In this paper, we propose a low power, cross-layer, collision-tolerant MAC scheme (CT-MAC) for an asynchronous one-hop WSN. The CT-MAC scheme can effectively extract the originally transmitted information by performing detection over the signals colliding at the base station (BS). The collision tolerance in the MAC layer is achieved by leveraging on the signal processing capability in the physical layer, where a new on-off accumulative transmission (OOAT) scheme is employed. With OOAT, each data symbol is transmitted in the form of multiple identical sub-symbols (accumulative transmission), and two consecutive sub-symbols are separated with a silence period (on-off transmission). The on-off transmission results in a low transmission duty cycle, which will reduce the probability of collision among the asynchronous nodes. At the mean time, with accumulative transmission, each data symbol is embedded in multiple signal samples received by the BS. Multi-dimensional signal in the time-domain enables the differentiation of signals colliding in the spatial-domain. A maximum likelihood sequence estimation (MLSE) detector with *time-varying* trellis structure is used to recover the transmitted information, and a matched filter bound of the error probability of the proposed system is derived. The CT-MAC with OOAT scheme significantly reduces transmission power by eliminating retransmission of colliding signals, utilizing the small duty cycle of the on-off transmission, and taking advantage of the time diversity enabled by accumulative transmission.

The remainder of this paper is organized as follows. The model and operations of CT-MAC with OOAT is presented in Section II. Section III presents an optimum MLSE detector with time-varying trellis structure for the proposed CT-MAC scheme. Simulation results are presented in Section IV, followed by conclusions in Section V.

II. Collision-Tolerant MAC with On-off Accumulative Transmission

The system model and operation of the proposed CT-MAC with OOAT is presented in this section.

A. System Model

Consider a WSN with N spatially distributed nodes and one BS. Data collected by the sensor nodes are delivered to the BS through a one-hop transmission. The sensor nodes are asynchronous, and there is neither central control nor explicit cooperation among the nodes.

To achieve collision tolerance in the MAC layer, the wireless nodes employ an OOAT scheme in the physical layer as shown in Fig. 1, where each data symbol is transmitted through M identical sub-symbols with a duration of T_0 each. On-off transmission is employed such that there is a silence period of duration $T_1 = (Q-1)T_0$ between two consecutively transmitted sub-symbols. With the OOAT scheme, each of the N nodes has a symbol period of $T_s = MQT_0$, and a transmission duty cycle of $\eta = \frac{1}{Q}$.

The OOAT scheme is defined by the ternary (N, M, Q). Fig. 1 shows a sample system with parameters $(N = 5, M = 3, Q = 4)$. Due to the asynchronism among nodes and the on-off transmission scheme, only a subset of the nodes will mutually interfere with each other. Therefore, the nodes can be divided into mutually orthogonal collision groups (CGs), where a CG contains all the nodes whose signals collide at the receiver, and there is no collision between nodes from different CGs. The number of nodes in a CG is defined as the collision order of the CG. For the $(5, 3, 4)$ system shown in Fig. 1, there are 3 CGs, $\mathcal{G}_1 = \{1\}$, $\mathcal{G}_2 = \{2, 4\}$, and $\mathcal{G}_3 = \{3, 5\}$, with collision orders being 1, 2, and 2, respectively.

The CT-MAC with OOAT attempts to recover the originally transmitted information by using signals colliding at the BS. Due to the mutual orthogonality among the CGs, signals transmitted in each CG can be detected separately. As an example, the received samples corresponding to signals from $\mathcal{G}_2$ of the system in Fig. 1 can be represented as in (1) shown at the top of the next page. In (1), $y(i)$ and $z(i)$ are the received sample and additive white Gaussian noise (AWGN) at sub-symbol index i, respectively, h_n is the fading coefficient between the node n and the BS, s_{nk} is the k-th symbol transmitted by the node n, and $\sqrt{P_n}$ is the instantaneous transmission power of the node n. It is assumed that the channel experiences quasi-static fading, *i.e.*, the fading coefficient is constant within one frame, and changes from frame to frame.

From (1), at any moment, there are at most $N_{\text{CG}} = |\mathcal{G}_2| = 2$ symbols interfering with each other. In addition, each symbol corresponds to $M = 3$ received samples. In general, for a CG with collision order N_{CG}, each received sample is the weighted superposition of symbols from up to N_{CG} different nodes. At the mean time, each symbol is embedded in M received samples. This is similar to a multiple-input multiple-output (MIMO) system with N_{CG} inputs and M outputs.

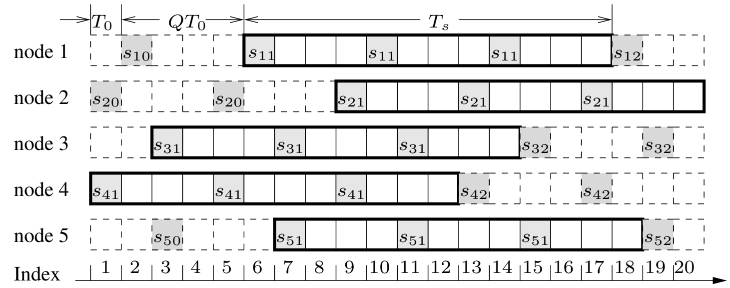

Fig. 1. a collision-tolerant MAC scheme with on-off accumulative transmission with $(N = 5, M = 3, Q = 4)$

B. Collision Tolerance

A WSN with OOAT is defined as collision-tolerant if the N_{CG}-dimension signal at the input can be recovered by the M-dimension signal at the output. We will study the collision tolerance of various systems by investigating the ternary (N, M, Q), which is critical to the performance of an OOAT system.

For an asynchronous system, each node starts its transmission at an arbitrary moment. As a result, the members of each CG and the corresponding collision order are random variables. We have the following Lemma regarding the statistical property of the collision order.

Lemma 1: Consider a (N, M, Q) CT-MAC system with OOAT. Let N_{CG} denote the collision order of a collision group. If all the N nodes are transmitting, then $N_{\text{CG}} - 1$ follows a binomial distribution, *i.e.*, $N_{\text{CG}} - 1 \sim B\left(N-1, \frac{1}{Q}\right)$. The average collision order is $\bar{N}_{CG} = \frac{N-1}{Q} + 1$.

Proof: Without loss of generality, consider sub-symbol index $[1, \cdots, Q]$, where each node will transmit exactly one sub-symbol. The users that occupy the same sub-symbol index belong to the same CG. For an asynchronous system, the occupied sub-symbol location for any user is uniformly distributed in $[1, Q]$. Given a node, the probability that there are exactly $(n-1)$ other nodes that collide with it is

$$P(N_{\text{CG}} = n | N, Q) = \binom{N-1}{n-1} \frac{1}{Q^{n-1}} \left(1 - \frac{1}{Q}\right)^{N-n}, \quad n = 1, \cdots, N. \tag{2}$$

Since the above expression is true for all the N nodes, $N_{\text{CG}} - 1 \sim B\left(N-1, \frac{1}{Q}\right)$. The average value of N_{CG} follows immediately from the definition of binomial distribution. ■

It can be seen from Lemma 1 that the collision order is directly related to N and Q, yet independent of M. The combination of N_{CG} and M determines the collision tolerance of a given system. We discuss the collision tolerance of the system under the following three cases.

Case I: $M \geq N_{CG}$. The system can be considered as a consistent overdetermined linear system with M observations and $N_{\text{CG}} \leq M$ unknown variables. As a result, there is always a unique solution. Thus a system with $M \geq N_{\text{CG}}$ is always collision-tolerant, for both analog communications and digital communications.

$$\begin{bmatrix} y(1) \\ y(5) \\ y(9) \\ y(13) \\ y(17) \\ y(21) \end{bmatrix} = \sqrt{P_2} \begin{bmatrix} h_2 & 0 & 0 \\ h_2 & 0 & 0 \\ 0 & h_2 & 0 \\ 0 & h_2 & 0 \\ 0 & h_2 & 0 \\ 0 & 0 & h_2 \end{bmatrix} \begin{bmatrix} s_{20} \\ s_{21} \\ s_{23} \end{bmatrix} + \sqrt{P_4} \begin{bmatrix} h_4 & 0 & 0 \\ h_4 & 0 & 0 \\ h_4 & 0 & 0 \\ 0 & h_4 & 0 \\ 0 & h_4 & 0 \\ 0 & h_4 & 0 \end{bmatrix} \begin{bmatrix} s_{41} \\ s_{42} \\ s_{43} \end{bmatrix} + \begin{bmatrix} z(1) \\ z(5) \\ z(9) \\ z(13) \\ z(17) \\ z(21) \end{bmatrix} \tag{1}$$

Case II: $M < N_{CG}$, s_{ni} is analog. The system is an underdetermined linear system with fewer observations than unknown variables. An underdetermined system has infinite analog solutions. Therefore, the analog value of s_{ni} cannot be uniquely determined, and the system is *not* collision-tolerant.

Case III: $M < N_{CG}$, s_{ni} is digital. If the system is digital with $s_{ni} \in \mathcal{S}$, where $\mathcal{S}$ is the modulation constellation set with cardinality $|\mathcal{S}| < \infty$, we can identify the transmitted symbols by intersecting the solution set of the underdetermined linear system with the vector constellation set $\mathcal{S}^{N_{CG}}$. If there is a unique solution in the intersection between these two sets, then the digital OOAT system is collision-tolerant, and it is *not* collision-tolerant otherwise. Numerical analysis shows that most digital systems are collision-tolerant with probability 1 for a large range of (N, M, Q). We will only focus on digital OOAT systems in this paper.

Based on the above analysis, we have the following corollary regarding the collision tolerance.

Corollary 1: Consider a (N, M, Q) CT-MAC system with OOAT. The probability that the system is collision tolerant is lower bounded by

$$P_{CT} \geq \sum_{n=1}^{M} \binom{N-1}{n-1} \frac{1}{Q^{n-1}} \left(1 - \frac{1}{Q}\right)^{N-n}. \tag{3}$$

This lower bound is exact for an analog communication system.

Proof: For both analog and digital communication systems, the system is guaranteed to be collision tolerant when $N_{CG} \leq M$. Thus the probability of collision tolerance is lower bounded by $P(N_{CG} \leq M)$, and (3) follows immediately from Lemma 1. Since an analog communication system is not collision tolerant if $N_{CG} > M$, the bound is exact for an analog communication system. ■

The OOAT scheme contributes to the collision tolerance from three aspects. First, the on-off transmission will reduce the collision order at the BS. Second, the transmission of M identical sub-symbols results in a M-dimension received signal in the time-domain, which can be used for the detection of the N_{CG}-dimension signal in the spatial-domain. Third, the spreading of the signals in the time-domain enables time diversity. It should be noted that the collision tolerance is achieved by exploiting the low data rate and long latency tolerance of a WSN. Larger values of M and Q lead to longer transmission latency or larger bandwidth, but better quality.

III. Optimum Detection in Digital OOAT System

An optimum receiver is developed in this section to recover the transmitted symbols from signals colliding at the BS.

A. Maximum Likelihood Sequence Estimation

With asynchronous nodes, the symbol from one node usually overlaps with two consecutive symbols from another node in the time-domain, *e.g.*, in Fig. 1, s_{41} from node 4 collides with both s_{20} and s_{21} from node 2. We denote such interference as co-channel intersymbol interference (CC-ISI) since it involves both co-channel interference between two nodes, and interference between symbols transmitted at different moments. Due to the presence of CC-ISI, each received sample is a superposition of multiple symbols from multiple nodes plus noise, and the composition of the received sample changes from sample to sample, *e.g.*, in Fig. 1 and (1), y_5 depends on s_{20} and s_{41}, yet y_9 depends on s_{21} and s_{41}. As a result, the CC-ISI structure changes with respect to time.

The presence of CC-ISI dictates that the optimum detection should be performed in terms of sequence-based detection instead of symbol-wise detection to avoid error propagation. Assume that the receiver performs detection over a window of KM samples, which can cover up to $(K+1)$ symbols from each node for a system with parameters (N, M, Q). Following a similar structure as (1), the system equation for an arbitrary CG with collision order N_{CG} can be written in a matrix format as

$$\mathbf{y} = \sum_{u=1}^{N_{CG}} \mathbf{H}_u \mathbf{s}_u + \mathbf{z}, \tag{4}$$

where $\mathbf{y} = [y(i_1), y(i_2), \cdots, y(i_{KM})]^T$ and $\mathbf{z} = [z(i_1), z(i_2), \cdots, z(i_{KM})]^T$ are the signal sample vector and noise sample vector, respectively, with the sample index $i_k = (k-1)M + 1$, and $\mathbf{s}_u = [s_{u0}, s_{u1}, \cdots, s_{uK}]^T$ is the symbol vector of the u-th node. The channel matrix, $\mathbf{H}_u \in \mathcal{C}^{KM \times (K+1)}$, is a block diagonal matrix represented by

$$\mathbf{H}_u = h_u \times \begin{bmatrix} \mathbf{1}_{u_0} & \mathbf{0}_{u_0} & \cdots & \mathbf{0}_{u_0} \\ \mathbf{0}_M & \mathbf{1}_M & \cdots & \mathbf{0}_M \\ \vdots & \ddots & \ddots & \vdots \\ \mathbf{0}_{u_1} & \cdots & \mathbf{0}_{u_1} & \mathbf{1}_{u_1} \end{bmatrix} \in \mathcal{C}^{KM \times K}, \tag{5}$$

where $\mathbf{0}_M$ is a $M \times 1$ all-zero vector, and $\mathbf{1}_M$ is a $M \times 1$ all-one vector. The values of u_0 and u_1 depend on the sampling timing offset between the transmitter and the receiver, and $u_0 + u_1 = M$. With the above system model, the optimum maximum likelihood sequence estimation (MLSE) decision rule can be written as

$$\hat{\mathbf{s}} = \underset{\mathbf{s}\in\mathcal{S}^{(K+1)N_{\text{CG}}}}{\text{argmax}} \; p\left(\mathbf{y}|\mathbf{H}_u, \mathbf{s}_u, u = 1, \cdots, N_{\text{CG}}\right) \qquad (6)$$

where $\mathbf{s} = [\mathbf{s}_1^T, \cdots \mathbf{s}_{N_{\text{CG}}}^T]^T$, with $(\cdot)^T$ denoting matrix transpose. It is assumed that the receiver has knowledge of the channel matrix, $\mathbf{H}_u$, which can be estimated by inserting pilot symbols at the transmitter.

B. Optimum Detection with Time-Varying Trellis

Due to the block diagonal structure of $\mathbf{H}_u$, the MLSE described in (6) can be performed by resorting to a trellis-based detection method such as the well known Viterbi algorithm [9]. In the proposed CT-MAC scheme, the time-varying CC-ISI results in a time-varying trellis structure.

As an example, consider collision group 2 of the $(5, 3, 4)$ system as described in Fig. 1 and (1). Binary phase shift keying (BPSK) modulation is employed in the system. With nodes 2 and 4 in the CG, the symbol vector is $\mathbf{s} = [s_2, s_4]^T$. For a collision group with collision order 2, the possible states are: $a = [-1, -1]$, $b = [-1, 1]$, $c = [1, -1]$, $d = [1, 1]$, $ab = [s_2 = -1]$, $cd = [s_2 = 1]$, $ac = [s_4 = -1]$, $bd = [s_4 = 1]$, and $abcd = \phi$. The state $abcd$ corresponds to a transition with no memory, *i.e.*, both the values of s_2 and s_4 change during the transition; the single-letter states, a, b, c, d, correspond to the transition where both s_2 and s_4 remain unchanged; the double-letter states, ab, cd, ac, bd, correspond to the transition where exactly one symbol changes.

The time-varying trellis structure of the first six transitions of the system in (1) are shown in Fig. 2. During the transition from $i_1 \rightarrow i_2$, it can be seen from (1) that the values of s_2 and s_4 remain unchanged. Therefor, the states remain unchanged as well. In this transition, there are 4 starting states, a, b, c, d. There is 1 branch originating from each starting state, and this branch leads to the same ending state. During the transition from $i_2 \rightarrow i_3$, the value of s_2 changes and s_4 stays the same. As a result, the 4 ending states, a, b, c, d, from the previous transition collapse into 2 starting states, ac and bd, corresponding to the 2 possible values of the unchanged symbol, s_4. The collapse of the states is illustrated as dashed lines in the trellis diagram. There are 2 branches fanning out from each state, with each branch corresponding to one of the 2 possible values of the changing symbol, s_2. As a result, there are 4 ending states, a, b, c, d, at the end of the transition $i_2 \rightarrow i_3$. Similarly, for the transition from $i_3 \rightarrow i_4$, the value of s_4 changes yet s_2 stays. In this case, the 4 ending states from the previous transition collapse into 2 starting states, ab and cd, corresponding to the 2 possible values of the unchanged symbol s_2. The new values of s_2 lead to 4 ending states at the end of the $i_3 \rightarrow i_4$ transition. The above procedure is repeated until the end of the detection window.

Once the trellis structure is established, the Viterbi algorithm can be slightly modified to suit the detection in a time-varying trellis. Each transition branch is associated with a

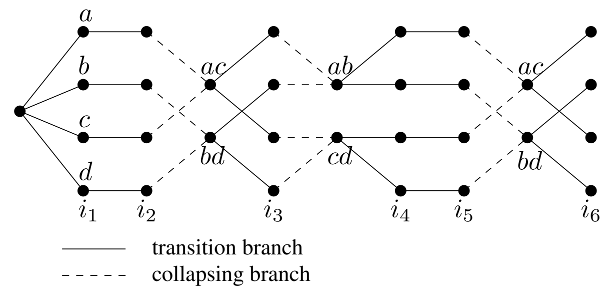

Fig. 2. Trellis structure of (1).

transition cost that is proportional to the likelihood function, $-\log p(y(i_k)|\mathbf{s})$, of the current transition. Each state is assigned a state cost, which is the accumulated cost of all branches leading to the current state. When 2 or more states collapse into a single state, only the collapsing branch originating from the state with the minimum accumulated state cost will survive, and all the other collapsing branches will be discarded. After discarding the non-survival collapsing branches, each state will have one and only one branch that ends at itself. Once the end of the detection window is reached, the sequence with the minimum accumulated distance is the detected sequence $\hat{\mathbf{s}}$. For a system with $|\mathcal{S}|$-ary modulation, each transition ends with $|\mathcal{S}|^{N_{\text{CG}}}$ states.

To summarize, each transition in a time-varying trellis involves two steps: 1) collapse the $|\mathcal{S}|^{N_{\text{GC}}}$ states into $|\mathcal{S}|^U$ states, where U is the number of symbols stay unchanged in the current transition; and 2) expand the $|\mathcal{S}|^U$ collapsed states into $|\mathcal{S}|^{N_{\text{GC}}}$ ending states by fanning out $|\mathcal{S}|^{(N_{\text{GC}}-U)}$ branches out of each collapsed state.

For a one-hop WSN, the time-varying MLSE detection is performed at the BS, which usually has a much higher processing power compared to the wireless nodes. On the other hand, the OOAT at the transmitter side involves only simple linear operations, and it can be easily employed by low cost low complexity wireless nodes with low power consumption.

C. Matched Filter Bound

A matched filter bound of the bit-error rate (BER) of the OOAT scheme is developed by ignoring the interference among the nodes. It was shown in [10] that MLSE receiver is asymptotically optimum in terms of interference cancellation. With the interference-free assumption, the received signals for a given node u can be written as

$$\mathbf{y}(k) = \sqrt{QP_s} \cdot \mathbf{1}_M \cdot h_u s_{uk} + \mathbf{z}(k), \qquad (7)$$

where P_s is the average transmission power and QP_s is the instantaneous transmission power due to the duty cycled transmission, $\mathbf{y}(k)$ and $\mathbf{z}(k)$ are, respectively, the received sample vector and noise sample vector with size being $M \times 1$, and s_{uk} is the k-th symbol of node u with unit energy.

The signal-to-noise ratio (SNR) of (7) can be written as $\gamma = MQ\gamma_0 \cdot |h_u|^2$, where $\gamma_0 = \frac{P_s}{\sigma_z^2}$ is the SNR without fading, with σ_z^2 being the noise variance. For systems with BPSK and

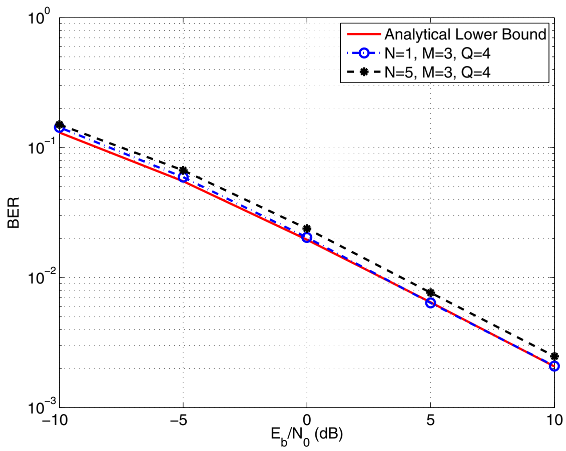

Fig. 3. Comparison between simulation results and analytical lower bounds.

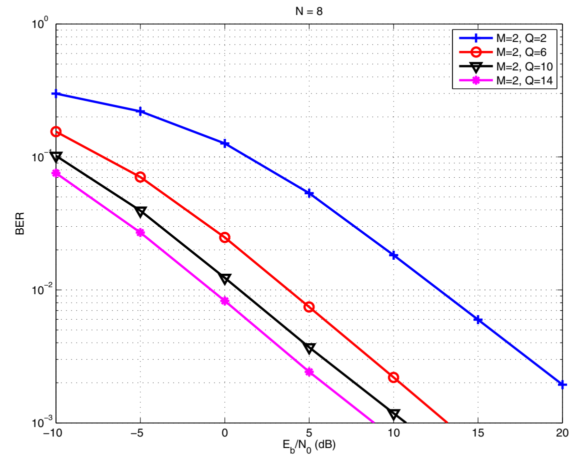

Fig. 4. Impacts of Q on the performance of an 8-user system.

Rayleigh fading, the error probability can be written as [10]

$$P(E) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\left[1+\frac{MQ\gamma_0}{\sin^2\theta}\right]^{-1}d\theta, \\ = \frac{1}{2}-\frac{1}{2}\sqrt{\frac{MQ\gamma_0}{1+MQ\gamma_0}}. \quad (8)$$

It will be shown through simulation that the matched filter lower bound in (8) is very tight, especially at high SNR.

IV. Simulation Results

We first investigate the BER performance of the $(5, 3, 4)$ system described in Fig. 1, and the result is shown in Fig. 3. For comparison, also shown in the figure are the analytical matched filter lower bound given in (8) and the BER of a one-user $(1, 3, 4)$ system. The expression given in (8) is exact for a one-user system due to the lack of collision. It can be seen that the analytical lower bound is very tight for the BER performance of the $(5, 3, 4)$ system, especially when $E_b/N_0 > 0$ dB. This results demonstrate that the optimum MLSE receiver with time-varying trellis structure can effectively remove the mutual interference among the users due to collision. As a result, the system is highly tolerant to collisions at the receiver.

Fig. 4 demonstrates the impact of Q on the performance of CT-MAC. The simulation is performed for a system with $(N = 8, M = 2, Q)$. Significant performance gains are observed as Q increases. At the BER level of 10^{-3}, increasing Q from 2 to 6, 10, or 14 results in a power saving of 10 dB, 15 dB, or 17 dB, respectively. Increasing Q results in 1) a smaller collision order; 2) a smaller duty cycle; and 3) a larger time diversity. The gain is achieved at the cost of longer delay. In practical system design, it is important to identify the optimum value of Q that strikes a balance between delay requirement and low power consumption.

V. Conclusion

A cross layer CT-MAC scheme was proposed to achieve low power communication in an asynchronous WSN. The collision tolerance in the MAC layer is enabled through physical layer operations, which include a simple OOAT scheme at the wireless nodes, and a MLSE detector with time-varying trellis structure at the BS. The on-off transmission reduces the collision probability at the receiver, and the accumulative transmission along with time-varying MLSE enable the recovery of the information from the colliding signals. The new scheme contributes to low power consumption through low duty cycle, tolerance to collision, and time diversity. Both analytical and simulation results showed that the newly proposed CT-MAC scheme can reliably operate at the presence of severe signal collision, even at a SNR below 0 dB.

Acknowledgments

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References

[1] J. P. Lynch, "An overview of wireless structural health monitoring for civil structures," *J. Math. Physical and Eng. Sci.*, June 2009.

[2] R. Cardell-Oliver, K. Smettem, M. Kranz, and K. Mayer, "Field testing a wireless sensor network for reactive environmental monitoring," in *Proc. IEEE Conf. Intelligent Sensors, Sensor Networks and Information Processing*, pp. 7 - 12, Dec. 2004.

[3] L. K. Au, W. H. Wu, M. A. Batalin, D. H. McIntire, and W. J. Kaiser, "MicroLEAP: energy-aware wireless sensor platform for biomedical sensing applications," in *Proc. Biomedical Circuits Syst. Conf.*, pp. 158 - 162, Nov. 2007.

[4] C. Schurgers, O. Aberthorne, and M. B. Srivastava, "Modulation scaling for energy-aware commun. systems," *Proc. Intern. Sym. Low Power Electronics and Design*, pp. 96 - 99, Sep. 2004.

[5] M. J. E. Golay, "Note on the theoretical efficiency of information reception with PPM," *Proc. IRE*, vol. 37, pp. 1031, Sep. 1949.

[6] A. El-Hoiydi, "Spatial TDMA and CSMA with preamble sampling for low power ad hoc wireless sensor networks," in *Proc. 7th Intern. Sym. Computers and Commun.*, pp. 685 - 692, 2002.

[7] J. Benson, T. O'Donovan, U. Reodig, and C. J. Sreenan, "Opportunistic aggregation over duty cycled communications in wireless sensor networks," in *Proc. Intern. Conf. Information Processing in Sensor Networks*, pp. 307 - 318, Apr. 2008.

[8] Q. Tu, "The low power wireless monitoring network with TDMA inquiry priority," in *Proc. 8th Intern. Conf. Signal Processing*, vol. 3, Nov. 2007.

[9] G. D. Forney, "the Viterbi algorithm," in *Proc. IEEE*, vol 61, pp. 268 C278, Mar. 1973.

[10] J. Wu and C. Xiao, "Performance analysis of wireless systems with doubly selective Rayleigh fading," in *IEEE Trans. Veh. Technol.*, vol. 56, pp. 721 - 730, Mar. 2007.