

COOPERATIVE MIMO COMMUNICATIONS IN WIRELESS SENSOR NETWORKS: ENERGY EFFICIENT COOPERATIVE MAC PROTOCOL

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Abstract

Multiple sensor nodes can be used to transmit and receive cooperatively and such a configuration is known as a cooperative Multiple-Input Multiple-Output (MIMO) system. Cooperative MIMO systems have been proven to reduce both transmission energy and latency in Wireless Sensor Networks (WSNs). However, most current work in WSNs considers only the energy cost for the data transmission component and neglects the energy component responsible for establishing a cooperative mechanism. In this work, both transmission and circuit energies for both components are included in the performance models. Furthermore, in previous work, all sensor nodes are assumed to be always on which could lead to a shorter lifetime due to energy wastage caused by idle listening and overhearing. Low duty cycle MAC protocols have been proposed to tackle this challenge for non-cooperative systems. Also in this work, we propose a new cooperative low duty cycle MAC protocol (CMAC) for two cooperative MIMO schemes: Beamforming (CMACBF) and Spatial Multiplexing (CMACSM). Performance of the proposed CMAC protocol is evaluated in terms of total energy consumption and packet latency for both synchronous and asynchronous scenarios. All the required energy components are taken into consideration in the system performance modeling and a periodic monitoring application model is used. The impact of the clock jitter, the check interval and the number of cooperative nodes on the total energy consumption and latency is investigated. The CMACBF protocol with two transmit nodes is suggested as the optimal scheme when operating at the 250 ms check interval with the clock jitter difference below $0.6T_b$ where T_b is the bit period

corresponding to the system bit rate.

Keywords: Cooperative Transmission, MIMO Technique, Low Duty Cycle MAC Protocol, Wireless Sensor Network

I. INTRODUCTION

Multi-hop communication has been claimed to improve energy efficiency of wireless networks. The intuition behind this claim is that, as the attenuation of radio signals with distance is at least quadratic in most environments (and usually larger), it takes less energy to use relays instead of using direct communication. So, shortening the distance between the nodes can significantly reduce the transmission energy required. However, as described in [1], the fact that multi-hop communication necessarily saves energy in WSNs is a misconception. The total energy consumption in the network should be considered including the energy consumed by the electronic circuitry in source, relay and destination nodes, and not only the radiated energy since the electronics circuits' energy consumption is comparable to or even dominates the transmission energy in short range communications [2].

To reduce total energy consumption, spatial diversity characteristics between nodes can be exploited to cooperatively transmit and receive information.

Such transmission and reception strategies, known as cooperative MIMO communications, have been proposed to provide higher reliability and reduction in both transmission energy and electronics circuits' energy in WSNs. As suggested in [2], energy savings and delay reduction can be achieved for transmission distances larger than a certain distance threshold and with the use of a suitable modulation scheme. Authors in [3] investigated the optimal cooperative MIMO schemes with Space-Time Block Coding (STBC) techniques where also both transmission and circuit energies were considered. Similar investigations have been done with different cooperative MIMO schemes such as the spatial multiplexing scheme in [4]. Performance of cooperative MIMO schemes has been found to depend on the operating distances and the number of cooperative nodes. In addition, some researchers considered the impact of imperfect synchronisation due to clock jitter on the performance of cooperative MIMO systems [5-8] and performance of cooperative MIMO schemes has also been found to depend on the clock jitter difference between cooperating nodes in addition to the operating distances and the number of cooperative nodes. Hence to achieve energy efficient operation, cooperative MIMO schemes must operate below a certain clock jitter threshold and above a certain distance threshold.

Previous work did not consider the energy cost in establishing cooperative mechanisms (cooperative nodes selection and local information exchanges) which could be significant for the total energy consumption in WSNs. Subsequent investigations in [9] have taken into consideration the energy cost for establishing a cooperative mechanism. The most important observation is that the cooperative MIMO system with the spatial multiplexing scheme is more energy efficient at a lower transmission power region than the non-cooperative Single-Input Single-Output (SISO) scheme. This counter-intuitive finding is due to the fact that the energy cost of

cooperative mechanism establishment becomes dominant as the transmission energy becomes higher. However, this work excluded the circuit energy consumption as it made the assumption that the energy consumed by the sensor nodes in the non-cooperative SISO system that are not transmitting is the same as that of the nodes transmitting in the cooperative MIMO system. This assumption is valid if the circuit energy for transmitting, receiving and idle listening is the same [10] and the transceiver is always on. However, always on sensor nodes may suffer a shorter lifetime due to energy wastage due to idle listening and overhearing.

Currently the idle listening and overhearing problems are tackled by equipping Medium Access Control (MAC) protocols with periodic wake-up mechanisms or also known as low duty cycle mechanism. Another approach is to use a wake-up radio mechanism [11, 12]. However, the latter is more difficult to implement due to hardware complexity and tight synchronisation requirements. It is important to note that the design requirements of WSN MAC protocols are completely different from the MAC protocols for traditional wireless networks. WSN MAC protocols trade off throughput, latency and fairness for energy efficient operation. Low duty cycle MAC protocols have been designed to provide energy efficient operation by combating the idle listening and overhearing problems that exist in systems with always on transceivers. A MAC employs a periodic wake-up mechanism where a sensor node enters into the sleep mode whenever there is no transmit or receive activity. In this way, the energy consumed for idle listening and overhearing can be reduced.

Most of the low duty cycle MAC protocols have been proposed for non-cooperative SISO systems. However, a low duty cycle MAC protocol may be also very useful for cooperative MIMO systems to avoid the idle listening and overhearing problems.

All the energy costs associated with transmission, reception, idle listening, establishing a cooperative mechanism, sleep, etc must be included in performance modeling of cooperative MIMO systems in order to find the optimal MIMO scheme.

The rest of the paper is organised as follows. In the next section, we briefly describe the related work. Section 3 describes the system model considered in this paper and explains the low duty cycle protocols that we propose for cooperative transmission. Section 4 models the system performances and presents the analytical results for the two MIMO schemes (BF and SM) in terms of total energy consumption and latency. Finally, in Section 5 we conclude the paper.

II. RELATED WORK

Cooperative MIMO has been proposed as a transmission strategy to combat the fading problem in WSNs to reduce the retransmission probability and lower the transmission energy. Among the earliest work on cooperative MIMO in WSNs is the analysis of the STBC scheme in [13-14] to achieve lower Bit Error Rate (BER) and significant energy savings. The work in [13] is continued with the implementation of the Low-Energy Adaptive Clustering Hierarchy (LEACH) MAC protocol for clustered-based architectures [6-8]. The combination of STBC and the LEACH scheme resulted in a significant improvement in transmission energy efficiency compared to the Single-Input Single Output (SISO) scheme.

Further study was conducted in [2] to compare the performance of STBC and various SM schemes such as Vertical Bell Labs Layered Space-Time (VBLAST) and Diagonal BLAST. In this work, LEACH MAC was also utilized and lower transmission energy and latency were achieved against the SISO scheme. However, the centralized architecture leads to energy wastage and higher latency compared to a distributed architecture.

On the other hand, the implementation of a distributed architecture needs to consider synchronisation issues. Thus a practical cooperative MIMO scheme for distributed asynchronous WSNs is needed. For example, a transmit Maximum Ratio Combiner (MRC) scheme is suggested to be more tolerant to the jitter difference than the Alamouti STC scheme in network with imperfect transmitting nodes synchronisation, as discussed in [5].

Moreover, a practical MAC that can suit cooperative transmission in distributed sensor network is required. Also a combination of a practical MAC protocol and an efficient MIMO scheme for cooperative transmission leads to a more energy efficient and lower latency cooperative MIMO system. A combination of a MAC protocol and a virtual SM scheme for cooperative MIMO transmission has been proposed in [9] where the combined scheme achieves significant energy efficiency and lower latency.

Further study has been done in [15] evaluating the MAC protocol in [9] using the other two cooperative schemes: BF and Space-Time Block Coding (STBC). The authors in [15] proposed that the optimal scheme for the cooperative always on MAC (CMAC_{ON}) is the BF scheme with $M = 2$. However, the MAC protocols for all the schemes considered the transceivers as always being on and the networks are perfectly synchronised. Although the transmission energy is reduced and the deep fading threat is reduced, the idle listening and overhearing problems are not tackled in the previous research work. Also the asynchronous scenario due to clock jitter is not considered.

Duty cycle mechanisms have been proposed to tackle the idle listening and overhearing problems. However, most of the duty cycle MAC protocols are designed for non-cooperative SISO schemes. Polastre in 2004 introduces B-MAC or Berkeley MAC [16]. The protocol is a

variant of Carrier Sense Multiple Access (CSMA) with a variant of duty cycle mechanism known as preamble sampling. The preamble sampling is improved with a selective sampling method where only energy above the noise floor is considered as useful. However B-MAC experiences a long preamble problem which leads to higher transmission and reception powers.

In order to reduce the long preamble problem, X-MAC [17] proposed the use of a series of short preamble packets with the destination address embedded in the packet. The X-MAC protocol provides more energy efficient and lower latency operation by reducing the transmission energy and period burdens, idle listening at the intended receiver and overhearing by the neighbouring nodes. One concern is that the gaps between transmissions of a series of preamble packets can be mistakenly understood by the other contending nodes as an idle channel and they would start to transmit their own preamble packets which can lead to collision. One solution is to ensure that the length of the gaps must be upper bounded by the length of the listen interval.

In the same year, SpeckMAC [18] was introduced as a variation of B-MAC with the idea of redundant transmission of short packets and an embedded destination address. There are two variants: SpeckMACBack-off (SpeckMAC-B) and SpeckMAC-Data (SpeckMAC-D). SpeckMAC-B sends short wake-up frames with an embedded target destination address many times. The problem with this scheme is that the sender wastes its transmission power by still sending the short frames although the receiver has already received it. Meanwhile, SpeckMAC-D sends the data packet which is preceded with a short preamble many times until the packet hits the receiver.

A comprehensive comparison study has been done [19] between the SpeckMAC variants which are based on different

traffic types in terms of energy efficient operation. The results demonstrated that SpeckMAC-D is more energy efficient than SpeckMAC-B when broadcast packets are transmitted. SpeckMAC-B, on the other hand, is more energy efficient when unicast packets are transmitted. Later, the SpeckMAC Hybrid or SpeckMAC-H protocol [19] was proposed combining the advantages of each of the SpeckMAC variants. SpeckMAC-H adopts an adaptive approach where the sender selects which SpeckMAC variant to be used depending on the current traffic type. In this way, the energy consumption can be reduced significantly but the excess latency problem is still not addressed.

In this work, we propose redundant transmission of Ready-to-Send (RTS) and Clear-to-Send (CTS) packets to hit the intended receiver. The cyclic RTS-CTS transmission scheme is used also for other purposes such as collision avoidance, cooperative nodes selection and channel state information (CSI) sharing between nodes. A combination of low duty cycle MAC with cyclic RTS-CTS transmission scheme is believed to reduce further the energy consumption and packet latency in cooperative MIMO transmission. In addition, an imperfect synchronisation scenario due to clock jitter differences is investigated.

The major contribution of this work is the proposal of CMAC with an embedded duty cycle mechanism which implements a cyclic RTS-CTS transmission scheme and acknowledgement (ACK) reply to ensure higher reliability. The CMAC is suggested to be used with two cooperative schemes: optimal BF and Spatial Multiplexing. We compare the performance of both these schemes in terms of energy consumption and latency. We also include a comparison with CMACON, B-MAC and always on SISO MAC. The impact of the jitter difference, the check interval and the number of cooperative nodes on the total energy consumption and latency for both synchronous and asynchronous scenarios are investigated.

III. SYSTEM MODEL

The baseline system for cooperative MIMO communication with the transceivers being always on is equipped with CMACON protocol as proposed and evaluated in [9]. Meanwhile, the baseline system for cooperative MIMO with a periodic wake-up cycle for the transceiver is equipped with the CMAC protocol as proposed and explained in subsection A. The baseline MAC for the SISO scheme with the transceiver being always on is CSMA-CA with RTS-CTS and ACK packets transmissions. For simplicity of notation, we denote the SISO scheme with this MAC protocol as the SISO always on protocol or SISOON protocol.

Also in this work we consider the impact of imperfect synchronisation which is caused by clock jitter alone. The detailed modelling of the impact of clock jitter is given in subsection B.

The network configurations for all the schemes considered in this work are as shown in Figures 1 and 2. The network is assumed to be distributed without any infrastructure. A new node can join or leave the network at any time because the knowledge of neighbours is not important due to the fact that the selection of cooperative nodes is done during the control packets communication. We assume that there are M cooperative transmitting nodes and one receiving node. A special case for the spatial multiplexing scheme is used where the number of the cooperative receivers is assumed to be N . Both the source and destination nodes have n neighbours in their vicinity. The distance between the cooperating nodes either at the transmitting or receiving side is assumed to be very small compared to the distance between the source node and the destination node, d . In the case of the cooperative BF scheme, the channel information is estimated and optimized from the CTS packet by all the M nodes. As for the cooperative SM scheme, the recovered data from $N-1$ nodes is forwarded to the destination node. Both

schemes utilize a Maximum Likelihood (ML) detector and use a coherent receiver.

A. Protocol Description

The proposed CMAC protocol combines the advantages of the cooperative MAC with always on radios and a preamble sampling mechanism. The basic structure of the protocol is given in Algorithm 1. A node may respond to three events for the case of the BF scheme (CMACBF) and to four events for the case of the SM scheme (CMACSM). In case a node has a data packet to send where the node is acting as the source node, the basic operations for both schemes are shown in Algorithm 2.

A node starts by sending RTS packets followed by an inter-frame spacing (IFS) for a period of the length of the check interval, T_i after sensing the channel idle. When a CTS packet is received, the source sets a timer to wake up later (the sleep duration is $T_i - T_{cts} - T_{transient}$) in order to transmit a broadcast packet at source (BS) immediately followed by the data packet (DATA), to its $M-1$ neighbours. Transmission of BS and DATA packets occurs at low transmission power. The BS packet is broadcasted by the source node to recruit its neighbours for cooperative transmitting operation and the DATA packet is the original data packet provided by the sensor device. When the sending timer expires (included in the BS packet), M nodes cooperatively transmit the data packet to the destination. After cooperatively transmitting the data, the source waits for an ACK packet. If an ACK is not received, the whole process is repeated. The number of RTS and CTS packets to be transmitted is given by:

$$R = \frac{T_i + T_{ifs_rts}}{T_{rts} + T_{ifs_rts}} \text{ and } C = \frac{T_i + T_{ifs_cts}}{T_{cts} + T_{ifs_cts}} \quad (1)$$

where T_{rts} , T_{cts} , T_{ifs_rts} , and T_{ifs_cts} are the duration of one RTS and CTS packet and the IFS intervals for RTS and CTS, respectively. The latter are given as:

$$T_{ifs_rts} = T_{ifs_cts} \leq T_{listen} \quad (2)$$

where the value T_{listen} is given in [16]. The operation of the destination node is shown in Algorithm 3 for both schemes. On receiving the RTS packet, the destination estimates the time to wake up in order to transmit CTS packets followed by IFS for a period of the length of the check interval, T_i . The sleep duration is $T_i - (SeqNum \times Trts + (SeqNum-1) \times Tifs_rts) - Ttransient$. After all the CTS packets are transmitted, the destination sets the timer to wake up at $TBs + Tdata - Ttransient$ to receive the data packet. In the case of the SM scheme, the destination broadcasts the broadcast packet BR at the receiver (BR packet is broadcasted by the destination to recruit its neighbours for cooperative receiving operation.) first and then goes to sleep for the duration of $TBs + Tdata - TBr - Ttransient$. After receiving the data packet, the destination sends an ACK packet immediately. In the case of the SM scheme, the destination waits for its neighbours to forward the data packets and does the final decoding of the packet based on all the received copies of the data packet from its neighbours.

The operations of cooperative sending and receiving nodes are shown in Algorithm 4 and 5. The selection of cooperative nodes is done during the control packets transmission where a node which receives RTS is informed to wake up at $T_i - (SeqNum \times Trts + (SeqNum-1) \times Tifs_rts) - Ttransient$ to receive CTS. The time waiting for CTS packet is denoted as $Twfcts$. If a node receives CTS, it is informed to wake up at $T_i - Tcts - Ttransient$ to receive BS for both schemes and BR for the SM scheme. The time waiting for the BS packet is denoted as $Twfbsdata$. The time waiting for the BR packet is the same as the time waiting for the BS packet. A node is chosen to be one of the cooperative nodes when it receives the broadcast packet. By using this mechanism, we can ensure that the network is scalable and no prior knowledge about neighbours is required for cooperative transmitting and receiving. Also, any node which

does not receive CTS after receiving RTS or does not receive a broadcast packet after receiving CTS needs to go to sleep. This mechanism avoids the problems of hidden nodes. The timers' settings are described in more detail in the timing diagrams in Figures 3 and 4 for the BF and SM schemes, respectively.

Algorithm 1: Cooperative MIMO MAC Protocol

STATE: LISTEN *node listens to the channel after it wakes up*
 if Packet ready to be sent then
 go to Algorithm 2
 end if
 if receive RTS then
 go to Algorithm 3
 end if
 if receive BSDATA then
 go to Algorithm 4
 end if
 if receive BR then
 go to Algorithm 5
 end if

Algorithm 3: Node is the destination for BF scheme

STATE: SLEEP *receives RTS and sets timer to wake up*
 STATE: CTS *sends CTS packet for a period of check interval*
 STATE: SLEEP *the node sets timer to wake up and goes to sleep*
 if data packet is received then
 go to STATE: ACK
 else if
 go to STATE: LISTEN
 STATE: ACK *node sends ACK packet*
 go to STATE: LISTEN

Algorithm 3: Node is the destination for SM scheme

STATE: SLEEP *receives RTS packet and sets timer to wake up*
 STATE: CTS *sends CTS packet for a period of check interval*
 STATE: BR *sends broadcast packet to neighbours*
 STATE: SLEEP *sets timer to wake up and goes to sleep*
 if data packet is received then
 go to STATE: COLLECTION
 else if
 go to STATE: LISTEN
 STATE: COLLECTION *set timer to wait for data packets*
 if packet not received correctly then
 go to STATE: LISTEN
 end if
 STATE: ACK *node sends ACK packet*
 go to STATE: LISTEN

Algorithm 4: Cooperative sending node

STATE: COOPERATIVE_SENDING *nodes transmit data packet when sending timer expires*
 go to STATE: LISTEN *listens for channel activity*

Algorithm 5: Cooperative receiving node

STATE: COOPERATIVE_RECEIVING *set expiration timer*
 if data packet received then
 go to STATE: COLLECTION
 else if
 go to STATE: SLEEP *after timeout*
 end if
 STATE: COLLECTION *sends data to destination node*
 go to STATE: SLEEP

B. Timing Error Model

We consider the impact of asynchronous scenario which is caused by clock jitter alone. Each cooperative sending nodes experiences clock jitter with the jitter around a reference clock T_{0v} denoted as T_j^m where $m = 1, 2$. The worst case scenario is considered here with only two cooperative transmitting nodes where the clock jitters are fixed at the extreme ends,

$$T_j^1 = -\frac{\Delta T_b}{2}, T_j^2 = +\frac{\Delta T_b}{2} \text{ where } 0 \leq \Delta T_b \leq T_b \text{ and } T_b$$

is the bit duration. Thus the clock jitters difference is $\Delta T_j = T_j^1 - T_j^2 = \Delta T_b$. The effect of asynchronous scenario can be modelled as a degrading function of the bit period which consequently degrades the received bit energy. Therefore the timing error as a function of the bit period and clock jitters difference is given as:

$$T_c = T_b - \Delta T_j. \quad (3)$$

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed cooperative low duty cycle MAC protocol in terms of energy consumption and packet latency for a wireless sensor network with periodic monitoring sampling application.

A. Energy Consumption

We consider a periodic sampling application with a uniform sampling period, T_s which has been discussed in detail in [16]. In general, the energy consumed by a sensor node can be categorized into five major parts [2]: energy expended during data sampling by sensor, E_{sensor} , energy expended during running the transceiver circuits, E_c , energy expended during packet transmission, E_v , energy expended during packet reception, E_r , and energy expended while idle listening, E_{idle} . For the case of the system with the CMAC protocol, additional energy must be considered:

energy expended during sleeping, E_{sleep} , listen energy after waking up, E_{listen} and transient energy, $E_{\text{transient}}$. The cooperative mechanism establishment energy cost is included in the transmission and reception energy models. Therefore, all the energy components must be considered when comparing the total energy consumption of the cooperative MIMO and SISO transmission schemes.

In this subsection, three analytical models are developed and analysed: SISO_{ONV}, CMAC_{ON} with the optimal BF scheme and CMAC with 2 variants, CMAC_{BF} and CMAC_{SM}. The total energy consumption of each model is analyzed and compared and the detail modelling for synchronous scenario can be obtained from [20] and for asynchronous scenario it is given in Appendix A. The retransmission rate is modelled as a function of PER where the detailed models and analysis can be found in [15] for the synchronous scenario and in Appendix B for the asynchronous scenario.

B. Packet Latency

As we noted, each packet transmission in cooperative transmission requires more steps which introduces more overhead. These steps may increase packet delays. However, the reduction of PER as the diversity gain increases from the cooperative MIMO exploitation can reduce the retransmissions rates which in turn can reduce packet latency. Previous work in [15] models packet latency performance for the non-cooperative SISO system. Comparison is then made with the models developed for the cooperative MIMO systems as shown in Appendix C. In addition to the delay incurred as calculated and analysed in [15] and Appendix C for CMAC_{ON} with both BF and SM cooperative schemes, the cyclic RTS-CTS transmission scheme periods which are calculated in Equation (1) are included. Also, the IFS periods for both RTS and CTS packet transmissions as calculated in Equation (2) are included.

C. Performance Results and Discussions

All the important parameters for energy consumption modelling are listed in [2, 9, 15, 16 and 21] with the times taken to transmit and receive 1 bit, $T_{rx,b}$ and $T_{rx,b}$ fixed at $4 \mu s$ corresponding to the bit rate of the system. The values of the system parameters used in Figures 14 and 15 for latency analysis are as follows: $T_{rts} = 0.52 \text{ ms}$, $T_{cts} = 0.44 \text{ ms}$, $T_{ack} = 0.432 \text{ ms}$, $T_{Bs} = 4.528 \text{ ms}$, $T_{Br} = 0.432 \text{ ms}$, $T_{data} = 4.096 \text{ ms}$, $T_{col} = 32.8 \text{ ms}$, and T_{wfac} for SM scheme = 70 ms [9] and T_{wfac} for BF scheme = 0.864 ms [22].

We can see in Figure 5 that both CMAC and $CMAC_{ON}$ outperform B-MAC and that the $CMAC_{BF}$ is more energy efficient than $CMAC_{SM}$ with two transmitting nodes for all the sampling periods. If we let the sampling period be long enough, the performance difference between CMAC and B-MAC should be reduced at the same check interval. Thus, we can deduce that CMAC is more energy efficient than B-MAC at shorter sampling periods which makes CMAC more practical for applications with frequent sampling periods.

As shown in Figure 6, B-MAC has the optimal check interval at 5 ms for the 5 minutes sampling period. We can expect that the optimal check interval gets higher when the sampling period gets higher. As measured at 10 minutes sampling period, the optimal check interval is 7 ms with 2 ms increases. The same observation is applied for CMAC as shown in Figure 7. Furthermore from Figure 6, we can observe that below 3 ms , both B-MAC and CMAC suffer higher transient energy which puts the lower bound or lower constraint on the operating check interval. Clearly, above 7 ms , CMAC outperforms both $CMAC_{ON}$ and B-MAC. B-MAC may suffer from higher transmission power due to a longer preamble packet as the check interval gets higher. Interestingly, $CMAC_{SM}$ has the same optimal check interval with $CMAC_{BF}$ for various

sampling periods as shown in Figure 7.

Figure 8 shows the impact of M on the energy consumption of CMAC and $CMAC_{ON}$. We can observe that the increase of energy consumption is small as M increases even when we increase M from 2 to 10 nodes. As long as the nodes are operating within an optimal range during cooperative communication [3], the small circuit energy can be tolerated in a cooperative low duty cycle MIMO system. The impact of N is shown in Figure 9. As we observed earlier, increasing M does not have a significant impact on the total energy consumption for both schemes. Interestingly, we also observe that N does not have a significant impact on the total energy consumption. Therefore, as long as we can tolerate a little increase of circuit energy by increasing the number of M and N , then we can choose to use either the BF or SM scheme in a cooperative low duty cycle MIMO system. However, the optimal choice is still to use $CMAC_{BF}$ and to set $M = 2$ and this result agrees with the previous results in [15]. On the other hand, when we consider high-speed WSNs, obviously $CMAC_{SM}$ is the optimal choice.

Figure 10 shows the $CMAC_{BF}$ outperforms the other schemes below $0.8T_b$ at common transmission power above 40 mW . Figure 11 shows the $CMAC_{SM}$ suffers the timing error effect at above $0.9T_b$ where $SISO_{ON}$ outperforms $CMAC_{BF}$. Also we observe that B-MAC outperforms both $CMAC_{BF}$ and $CMAC_{ON}$ utilising the BF scheme with $0.9T_b$ at a lower check interval below 200 ms . A closer look at all the cooperative MAC schemes is shown in Figure 12 where the jitter difference is varied from $0T_b$ to $0.8T_b$. $CMAC_{BF}$ experiences 1.3 mJ/s increases between $0T_b$ and $0.8T_b$. The increase is still small when we compare it to $CMAC_{SM}$ and $CMAC_{ON}$ utilising the BF scheme with 4.6 mJ/s and 3.5 mJ/s increases, respectively.

The impact of the number of cooperative receiving nodes, N , in the cooperative SM scheme is shown in Figure 13. We

can reduce the energy cost from 4.6mJ/s increase to 0.2mJ/s increase when $N = 6$. As N gets higher, the circuit energy gets higher and thus the total energy consumption also gets higher. However, we can tolerate the small circuit energy at higher jitter differences as shown since CMAC_{ON} utilising the BF scheme with $N = 20$ at $0.8T_b$ has lower energy than CMAC_{ON} utilising the BF scheme with $N = 2$ at $0.8T_b$.

From all the observations, we suggest that CMAC_{BF} is the optimal choice below $0.9T_b$ clock jitter difference. As shown in Figures 14 and 15, B-MAC enjoys lower packet latency and outperforms the other schemes even when the diversity gain of the cooperative SM scheme is increased. CMAC_{ON} utilising the BF scheme outperforms B-MAC when the transmission power is higher than 50mW below $0.4T_b$. CMAC_{BF} with $0T_b$ suffers a slightly higher delay compared to B-MAC when the transmission power is 50mW. In order to maintain lower latency, as low as 50 ms, CMAC_{BF} must operate below $0.6T_b$ jitter difference.

V. CONCLUSION

In order to address the idle listening and overhearing problems in a system with the CMAC_{ON} protocol, we have proposed a new Cooperative low duty cycle MAC protocol (CMAC) for two cooperative MIMO schemes: optimal Beamforming (CMAC_{BF}) and Spatial Multiplexing (CMAC_{SM}). We have developed analytical models to evaluate total energy consumption and packet latency for both schemes. We have considered both synchronous and asynchronous scenarios. We have taken into consideration all the related energy costs (transmission, reception, idle listening, establishing cooperative mechanism, sleep, etc.) in the system performance modeling. We have applied the models for periodic monitoring applications.

We conclude that the new cooperative

low duty cycle MAC with the optimal Beamforming scheme (CMAC_{BF}) outperforms the other cooperative and SISO schemes in terms of total energy consumption with the number of cooperating nodes set to $M = 2$. In order to achieve both lower energy and lower latency, CMAC_{BF} must operate at $M = 2$ and with the clock jitter difference below $0.6T_b$. These results can be used to assist with the design of CMAC for multi-hop communication. Moreover, the trade-off relationship between energy efficient operation and latency can be utilised to find the optimal number of hops and the optimal number of cooperating nodes that should be involved in the transmission.

APPENDIX A: ENERGY CONSUMPTION MODELING

A. SISO System

The total energy consumption in the SISO system, in general, is given as:

$$E_{\text{siso}} = (E_{\text{rx}} + E_{\text{cr}}) + (E_{\text{tx}} + E_{\text{ct}}) + E_{\text{sensor}} + E_{\text{idle}} \quad (\text{A1})$$

where E_{rx} and E_{tx} are the energy spent during reception and transmission, and E_{cr} and E_{ct} are the energy spent by the receiver and transmitter circuits. The transmission energy model for the SISO system which includes both the radiated power and circuit power is the same as discussed in [15]. Consequently, the reception energy model can be obtained directly from the transmission energy model in [15].

The total time a node spends during successful transmission is given as:

$$T_{\text{tx}_s} = r_s \times (N_{\text{rts}} + N_{\text{cts}} + N_{\text{data}} + N_{\text{ack}}) \times T_{\text{tx}_b} \quad (\text{A2})$$

and the total time a node spends during unsuccessful transmission is given as:

$$T_{\text{tx}_u} = r_s \times (N_{\text{rts}} + N_{\text{cts}} + N_{\text{data}}) \times T_{\text{tx}_b} \quad (\text{A3})$$

where r_s is the sampling frequency and

can be obtained by the inverse of the sampling period, T_{rx_b} is the transmit period per bit, and N_{rts} , N_{cts} , N_{data} and are the lengths of the RTS, CTS, DATA and ACK packets.

The total time a node spends during successful reception is given as:

$$T_{rx_s} = r_s \times (n \cdot N_{rts} + n \cdot N_{cts} + N_{data} + N_{ack}) \times T_{rx_b} \quad (A4)$$

and the total time a node spends during unsuccessful reception is given as:

$$T_{rx_u} = r_s \times (n \cdot N_{rts} + n \cdot N_{cts} + N_{data}) \times T_{rx_b} \quad (A5)$$

where T_{rx_b} is the receive period per bit.

The total time a node spends idle for successful communication is given as:

$$T_{idle_s} = 1 - T_{tx_s} - T_{rx_s} - T_{sensor} \quad (A6)$$

and the idle time for unsuccessful communication is given as:

$$T_{idle_u} = 1 - T_{tx_u} - T_{rx_u} \quad (A7)$$

where T_{sensor} is the period of a sensor to start, initialise, and collect data as discussed in [16] and the value is given in [16, 21]. Thus, the total energy consumption for successful SISO system communication can be obtained as:

$$E_{siso_s} = (P_{pa} + P_{ct}) \cdot T_{tx_s} + (P_r + P_{cr}) \cdot T_{rx_s} + P_{idle} \cdot T_{idle_s} \quad (A8)$$

and the total energy consumption for unsuccessful SISO system communication can be obtained as:

$$E_{siso_u} = (P_{pa} + P_{ct}) \cdot T_{tx_u} + (P_r + P_{cr}) \cdot T_{rx_u} + P_{idle} \cdot T_{idle_u} \quad (A9)$$

Therefore, the total energy consumption for the SISO system can be modelled as a function of the retransmission rate:

$$E_{siso} = \left(\frac{P_{psiso}}{1 - P_{psiso}} \right) E_{siso_u} + E_{siso_s} + E_{sensor} \quad (A10)$$

where P_{psiso} is the packet error probability of the SISO system which can be obtained from [15] for synchronous scenario and Appendix B for asynchronous scenario.

B. Cooperative Always On MIMO System

In this subsection, we analyse total energy consumption for the optimal cooperative BF scheme with the CMAC_{ON} protocol as recommended in [15]. The transmission energy model for the cooperative always on MIMO system which includes the radiated power, circuit power and cooperative mechanism power is the same as discussed in [15]. Consequently, the reception energy model can be obtained directly from the transmission energy model in [15].

In order to provide better understanding about the energy models for cooperative MIMO systems in this work, we categorise both the transmission and reception total time into three categories which are based on packet types namely: control, cooperative mechanism and data categories.

The total time a node spends during successful control packet transmission is given as:

$$T_{tx_s\ control} = r_s \times (N_{rts} + N_{cts} + N_{ack}) \times T_{tx_b} \quad (A11)$$

and the total time a node spends during cooperative mechanism transmission for optimal BF scheme is given as:

$$T_{tx_Bdata} = r_s \times (N_{Bs} + N_{data}) \times T_{tx_b} \quad (A12)$$

and the total time a node spends during data packet transmission is given as:

$$T_{tx_data} = r_s \times M \times (N_{data}) \times T_{tx_b} \quad (A13)$$

Thus, the total time a node spends during successful transmission in cooperative always on MIMO system with optimal BF scheme can be given as:

$$T_{tx_s\ BF} = T_{tx_s\ control} + T_{tx_Bdata} + T_{tx_data} \quad (A14)$$

and the total time a node spends during unsuccessful transmission is given as:

$$T_{tx_u_BF} = T_{tx_s_BF} - (r_s \times N_{ack} \times T_{tx_b}) \quad (A15)$$

where N_{Bs} is the length of the broadcast packet at the source node. The total time a node spends during successful control packet reception is given as:

$$T_{rx_s_control} = r_s \times (n \cdot N_{rx} + n \cdot N_{cis} + N_{ack}) \times T_{rx_b} \quad (A16)$$

and the total time a node spends during cooperative mechanism reception is given as:

$$T_{rx_Bsddata} = r_s \times (M-1) \times (N_{Bs} + N_{data}) \times T_{rx_b} \quad (A17)$$

and the total time a node spends during data packet reception is given as:

$$T_{rx_data} = r_s \times (N_{data}) \times T_{rx_b}. \quad (A18)$$

Thus, the total time a node spends during successful reception in cooperative always on MIMO system with optimal BF scheme can be given as:

$$T_{rx_s_BF} = T_{rx_s_control} + T_{rx_Bsddata} + T_{rx_data} \quad (A19)$$

and the total time a node spends during unsuccessful reception is given as:

$$T_{rx_u_BF} = T_{rx_s_BF} - r_s \times (N_{ack}) \times T_{rx_b}. \quad (A20)$$

The total time a node spends idle for successful communication is given as:

$$T_{idle_s_BF} = 1 - T_{tx_s_BF} - T_{rx_s_BF} - T_{sensor} \quad (A21)$$

and the idle time for unsuccessful communication is given as:

$$T_{idle_u_BF} = 1 - T_{tx_u_BF} - T_{rx_u_BF}. \quad (A22)$$

Thus, the total energy consumption for successful cooperative always on MIMO system communication can be obtained as:

$$E_{BF_s} = (P_{pa} + P_{ct}) T_{tx_s_control} + (P_{paBs} + P_{ct}) T_{tx_Bsddata} + (P_{paBF} + P_{ct}) T_{tx_data} + (P_r + P_{cr}) T_{rx_s_control} + (P_{rBs} + P_{cr}) T_{rx_Bsddata} + (P_{rBF} + P_{cr}) T_{rx_data} + P_{idle_s} T_{idle_s_BF} \quad (A23)$$

and the total energy consumption for unsuccessful cooperative always on MIMO system communication can be obtained as:

$$E_{BF_u} = (P_{pa} + P_{ct}) T_{tx_u_control} + (P_{paBs} + P_{ct}) T_{tx_Bsddata} + (P_{paBF} + P_{ct}) T_{tx_data} + (P_r + P_{cr}) T_{rx_u_control} + (P_{rBs} + P_{cr}) T_{rx_Bsddata} + (P_{rBF} + P_{cr}) T_{rx_data} + P_{idle_u} T_{idle_u_BF} \quad (A24)$$

Therefore, the total energy consumption for the cooperative always on MIMO system can be modelled as a function of the retransmission rate:

$$E_{BF_on} = \left(\frac{P_{pBF}}{1 - P_{pBF}} \right) E_{BF_u} + E_{BF_s} + E_{sensor} \quad (A25)$$

where P_{pBF} is the packet error probability of the cooperative BF system which can be obtained from [15] for synchronous scenario and Appendix B for asynchronous scenario.

C. Cooperative Low Duty Cycle MIMO System

In this subsection, we analyse the total energy consumption for the cooperative BF and SM schemes equipped with the proposed cooperative low duty cycle MAC protocol. The only modifications on the total energy consumption model are the definition of the control packets intervals which should be depended on the length of the check interval where the R and C terms are included and the addition of sleep energy. Also, the idle listening cost still exists when a node is in listening and waiting states. The transient energy is included in the total listening energy cost as explained in [16].

The total time a node spends during successful control packet transmission in cooperative low duty cycle MIMO system is given as:

$$T_{rx_s_control} = r_s \times (R \cdot N_{rts} + C \cdot N_{rts} + N_{ack}) \times T_{rx_b}. \quad (A26)$$

The total time a node spends during cooperative mechanism transmission at the transmitting side for both BF and SM schemes in a cooperative low duty cycle MIMO system is the same as given by (A12). The total time a node spends during cooperative mechanism transmission at the receiving side by the SM scheme in a cooperative low duty cycle MIMO system can be given as:

$$T_{rx_Br} = r_s \times (N_{Br}) \times T_{rx_b} \quad (A27)$$

$$T_{rx_col} = r_s \times (N-1) \times \left(N_{data} \cdot T_{rx_b} + \left(\frac{\sum_{BE=1}^{\max BE} T_{BO} + T_{CCA}}{5} \right) \right) \quad (A28)$$

where N_{Br} is the length of broadcast packets at the destination node. T_{BO} , T_{CCA} and BE are the average back-off duration, the clear channel assessment (CCA) analysis duration and the back-off exponent value with all the values derived in detail in [22, 23].

The total time a node spends during data packet transmission for both BF and SM schemes in a cooperative low duty cycle MIMO system is the same as given by (A13). Thus, the total time a node spends during successful transmission for the BF scheme is the same as given in (A14) and the total time a node spends during successful transmission for the SM scheme in a cooperative low duty cycle MIMO system can be obtained as:

$$T_{rx_s_SM} = T_{rx_s_BF} + T_{rx_Br} + T_{rx_col} \quad (A29)$$

and the total time a node spends during unsuccessful transmission is the same as in (A15) for cooperative BF scheme and is given as:

$$T_{rx_u_SM} = T_{rx_s_SM} - (r_s \times N_{ack} \times T_{rx_b}) \quad (A30)$$

for the cooperative SM scheme.

The total time a node spends during

successful and unsuccessful receptions for both cooperative schemes are the same as in (A16) to (A20) with an addition for the total time of cooperative mechanism reception at the receiving side by the cooperative SM scheme which is given as:

$$T_{rx_Br} = r_s \times (N-1) \times N_{Br} \times T_{rx_b} \quad (A31)$$

$$T_{rx_col} = r_s \times (N-1) \times N_{data} \times T_{rx_b}. \quad (A32)$$

The total time a node spends idle for successful communication for both cooperative schemes is given as:

$$T_{idle_s_BF} = T_{ifs_rts} + T_{ifs_cts} + T_{wfcts} + T_{wfbsdata} \quad (A33)$$

$$T_{idle_s_SM} = T_{idle_s_BF} \quad (A34)$$

and the idle time for unsuccessful communication is given as:

$$T_{idle_u_BF} = T_{idle_s_BF} + T_{wfact} \quad (A35)$$

$$T_{idle_u_SM} = T_{idle_s_SM} + T_{wfact} \quad (A36)$$

where T_{wfcts} , $T_{wfbsdata}$ and T_{wfact} are the waiting for the CTS packet period, waiting for the BSDATA packet period and the waiting period for the ACK packet to arrive. The total time a node spends for sleeping for successful communication for both cooperative schemes is given as:

$$T_{sleep_s_BF} = 1 - T_{rx_s_BF} - T_{rx_s_SM} - T_{idle_s_BF} - T_{listen} - T_{sensor} \quad (A37)$$

$$T_{sleep_s_SM} = 1 - T_{rx_s_SM} - T_{rx_s_SM} - T_{idle_s_SM} - T_{listen} - T_{sensor} \quad (A38)$$

and the sleep time for unsuccessful communication is given as:

$$T_{sleep_u_BF} = 1 - T_{rx_u_BF} - T_{rx_u_BF} - T_{idle_u_BF} - T_{listen} \quad (A39)$$

$$T_{sleep_u_SM} = 1 - T_{rx_u_SM} - T_{rx_u_SM} - T_{idle_u_SM} - T_{listen} \quad (A40)$$

Thus, the total energy consumption for successful cooperative low duty cycle MIMO system communication can be obtained as:

$$\begin{aligned}
 E_{BF_s} = & (P_{pa} + P_{ct}) T_{tx_s_control} + (P_{paBs} + P_{ct}) T_{tx_Bsdata} + \\
 & (P_{paBF} + P_{ct}) T_{tx_data} + (P_r + P_{cr}) T_{rx_s_control} + \\
 & (P_{rBs} + P_{cr}) T_{rx_Bsdata} + (P_{rBF} + P_{cr}) T_{rx_data} + \\
 & P_{idle} \cdot T_{idle_s_BF} + P_{sleep} \cdot T_{sleep_s_BF} + E_{listen}
 \end{aligned} \quad (A41)$$

and

$$\begin{aligned}
 E_{SM_s} = & (P_{pa} + P_{ct}) T_{tx_s_control} + (P_{paBs} + P_{ct}) T_{tx_Bsdata} + \\
 & (P_{paBF} + P_{ct}) T_{tx_data} + (P_{paBr} + P_{ct}) T_{tx_Br} + \\
 & (P_{paBr} + P_{ct}) T_{tx_col} + (P_r + P_{cr}) T_{rx_s_control} + \\
 & (P_{rBs} + P_{cr}) T_{rx_Bsdata} + (P_{rSM} + P_{cr}) T_{rx_data} + \\
 & P_{idle} \cdot T_{idle_s_SM} + P_{sleep} \cdot T_{sleep_s_SM} + E_{listen}
 \end{aligned} \quad (A42)$$

and the total energy consumption for unsuccessful cooperative low duty cycle MIMO system communication can be obtained as:

$$\begin{aligned}
 E_{BF_u} = & (P_{pa} + P_{ct}) T_{tx_u_control} + (P_{paBs} + P_{ct}) T_{tx_Bsdata} + \\
 & (P_{paBF} + P_{ct}) T_{tx_data} + (P_r + P_{cr}) T_{rx_u_control} + \\
 & (P_{rBs} + P_{cr}) T_{rx_Bsdata} + (P_{rBF} + P_{cr}) T_{rx_data} + \\
 & P_{idle} \cdot T_{idle_u_BF} + P_{sleep} \cdot T_{sleep_u_BF} + E_{listen}
 \end{aligned} \quad (A43)$$

and

$$\begin{aligned}
 E_{SM_u} = & (P_{pa} + P_{ct}) T_{tx_u_control} + (P_{paBs} + P_{ct}) T_{tx_Bsdata} + \\
 & (P_{paBF} + P_{ct}) T_{tx_data} + (P_{paBr} + P_{ct}) T_{tx_Br} + \\
 & (P_{paBr} + P_{ct}) T_{tx_col} + (P_r + P_{cr}) T_{rx_u_control} + \\
 & (P_{rBs} + P_{cr}) T_{rx_Bsdata} + (P_{rSM} + P_{cr}) T_{rx_data} + \\
 & P_{idle} \cdot T_{idle_u_SM} + P_{sleep} \cdot T_{sleep_u_SM} + E_{listen}
 \end{aligned} \quad (A44)$$

Therefore, the total energy consumption for the cooperative low duty cycle MIMO system can be modelled as a function of the retransmission rate:

$$E_{BF} = \left(\frac{P_{pBF}}{1 - P_{pBF}} \right) E_{BF_u} + E_{BF_s} + E_{sensor} \quad (A45)$$

$$E_{SM} = \left(\frac{P_{pSM}}{1 - P_{pSM}} \right) E_{SM_u} + E_{SM_s} + E_{sensor} \quad (A46)$$

where P_{pBF} and P_{pSM} are the packet error probability of the cooperative BF and SM systems respectively which can be obtained from [15] for synchronous scenario and Appendix B for asynchronous scenario.

APPENDIX B: ERROR PERFORMANCE MODELING

We derive the two most important performance parameters to measure the channel condition and to evaluate the link reliability: BER and PER. Without Forward Error Correction (FEC), the relationship between Packet Error Rate (PER), Pp and BER, Pb is given by:

$$P_p = 1 - (1 - P_b)^{N_{data}} \quad (B1)$$

where N_{data} is the packet length in bits. Consider the case of BPSK modulation under quasi-static Rayleigh fading with fading gain h , experiencing a square law path loss without channel codes. In the SISO system, the conditional SNR is given by [24]:

$$\gamma_{bSISO} = \frac{P_t |h|^2 G_t G_r}{N_o M_l \left(\frac{4\pi d}{\lambda} \right)^2} \quad (B2)$$

where P_t is the transmission power, d is the distance between the sending and destination node, G_t and G_r are the transmission and reception antenna gain, λ is the carrier wave length, M_l is the link margin and N_o is single-sided thermal noise power spectral density (PSD) given as -171 dBm/Hertz. The probability density function (PDF) of γ_{bSISO} is given by:

$$p(\gamma_{bSISO}) = \frac{1}{\bar{\gamma}_{bSISO}} \exp \left(-\frac{\gamma_{bSISO}}{\bar{\gamma}_{bSISO}} \right) \quad (B3)$$

where $\bar{\gamma}_{bSISO}$ is the average SNR. Assume that $E[h^2] = 1$ [25], then the value of $\bar{\gamma}_{bSISO}$ is given by:

$$\bar{\gamma}_{bSISO} = \frac{P_t E[h^2] G_t G_r}{N_o M_l \left(\frac{4\pi d}{\lambda} \right)^2} = \frac{P_t G_t G_r}{N_o M_l \left(\frac{4\pi d}{\lambda} \right)^2} \quad (B4)$$

The average BER can be expressed as:

$$E_b [P_{bSISO}] = E_b \left[Q \left(\sqrt{2\gamma_{bSISO}} \right) \right] \quad (B5)$$

The upper bound of the average BER can be derived as [24]:

$$Q(\sqrt{2\gamma_{bSISO}}) = P(x \geq \sqrt{2\gamma_{bSISO}}) \leq \exp\left(-\frac{(\sqrt{2\gamma_{bSISO}})^2}{2}\right) \quad (B6)$$

$$E[Q(\sqrt{2\gamma_{bSISO}})] \leq E[\exp(-\gamma_{bSISO})]. \quad (B7)$$

The moment generating function of γ_{bSISO} is given by [24]:

$$\Phi(S) = E[\exp(\gamma_{bSISO}S)] = \frac{1}{S\bar{\gamma}_{bSISO}} \quad (B8)$$

$$E_h[P_{bSISO}] \leq E[\exp(-\gamma_{bSISO})] = \Phi(-1) = (1 + \bar{\gamma}_{bSISO})^{-1}. \quad (B9)$$

If there are M nodes in the sending group, the SNRs of optimal BF scheme for asynchronous scenario at the destination node can be given by:

$$\gamma_{bBF} = \sum_{k=1}^M |h_k|^2 \frac{P_r G_r G_r}{N_o M_l \left(\frac{4\pi d}{\lambda}\right)^2} \cdot \frac{T_c}{T_b} = \sum_{k=1}^M \gamma_{BFk} \quad (B10)$$

where γ_{BFk} is the instantaneous SNR on the k_{th} channel. The PDF of γ_{BFk} is:

$$p(\gamma_{BFk}) = \frac{1}{\bar{\gamma}_{BFk}} \exp\left(-\frac{\gamma_{BFk}}{\bar{\gamma}_{BFk}}\right). \quad (B11)$$

Assume that $E[\|h_k\|^2] = 1$ [25], then the value of $\bar{\gamma}_{BFk}$ for asynchronous scenario can be given by:

$$\bar{\gamma}_{BFk} = \frac{P_r E[\|h_k\|^2] G_r G_r}{N_o M_l \left(\frac{4\pi d}{\lambda}\right)^2} \cdot \frac{T_c}{T_b} = \frac{P_r G_r G_r}{N_o M_l \left(\frac{4\pi d}{\lambda}\right)^2} \cdot \frac{T_c}{T_b}. \quad (B12)$$

The moment generating functions of γ_{BFk} is [24]:

$$\Phi(S) = E[\exp(\gamma_{bBF}S)] = \prod_{k=1}^M \frac{1}{S\bar{\gamma}_{BFk}} \quad (B13)$$

$$E_h[P_{bBF}] \leq E[\exp(-\gamma_{bBF})] = \Phi(-1) = (1 + \bar{\gamma}_{bBF})^{-M} \quad (B14)$$

The average BER for the cooperative SM scheme in [9] is given as:

$$P_{bSM} = \sum_{k=N/2}^N \binom{N}{k} P_e^k (1 - P_e)^{N-k} \quad (B15)$$

$$P_e = E_h[P_{bMISO}] + E_h[P_{bSISO}] - E_h[P_{bSISO}] E_h[P_{bMISO}] \quad (B16)$$

where P_e is the error rate in each route and N is the number of nodes forming the reception group. The average SNR of the MIMO scheme in (B16) is the same as the average SNR of the cooperative MISO BF scheme [9]. Thus we assume that the average BER is the same for both schemes. Table in [15] lists the system parameters used for evaluating BER performance of the cooperative MIMO schemes.

APPENDIX C: PACKET LATENCY MODELING

A. SISO System

For SISO communication, T_{rts} , T_{cts} , T_{data} and T_{ack} are the transmission periods for the RTS, CTS, DATA and ACK packets. The period with a successful transmission attempt is given as:

$$T_{s_siso} = T_{rts} + T_{cts} + T_{data} + T_{ack} \quad (C1)$$

and the period with an unsuccessful transmission attempt is given as:

$$T_{u_siso} = T_{rts} + T_{cts} + T_{data} + T_{wait} \quad (C2)$$

where T_{wait} is the duration for which the sender waits for an ACK packet. The packet transmission delay is then given as:

$$T_{d_siso} = \left(\frac{P_{psiso}}{1 - P_{psiso}}\right) T_{u_siso} + T_{s_siso}. \quad (C3)$$

where P_{psiso} is the packet error probability of the SISO system which can be obtained from [15] for synchronous scenario and Appendix B for asynchronous scenario.

B. Cooperative Always On MIMO System

In addition to the delay incurred as calculated in the previous subsection, the broadcast packet transmission from the source node to its neighbours introduces

a broadcast transmission period, TBs in cooperative BF and SM transmissions. The transmission period of cooperative BF and SM data packets is the same as that for the SISO system due to the fact that the packet size and the modulation scheme are the same. The duration of a successful transmission attempt for BF scheme is given as:

$$T_{s_M} = T_{rts} + T_{cts} + T_{Bs} + T_{data} + T_{ack} \quad (C4)$$

and the period with an unsuccessful transmission attempt for BF scheme is given as:

$$T_{u_M} = T_{rts} + T_{cts} + T_{Bs} + T_{data} + T_{wait} \quad (C5)$$

The expected packet transmission delay is then given by:

$$T_{d_M} = \left(\frac{P_{pBF}}{1 - P_{pBF}} \right) T_{u_M} + T_{s_M} \quad (C6)$$

where P_{pBF} is the packet error probability of the cooperative BF system which can be obtained from [15] for synchronous scenario and Appendix B for asynchronous scenario.

For the case of cooperative MIMO SM, we introduce the delay for the broadcast transmission time of a recruitment message sent by the destination node, T_{Br} and the delay for the time required by the cooperating receiving nodes ($N-1$) to send the data to the destination, T_{col} . The duration of a successful transmission attempt for SM scheme is given as:

$$T_{s_SM} = T_{s_M} + T_{Br} + T_{col} \quad (C7)$$

and the period with an unsuccessful transmission attempt for SM scheme is given as:

$$T_{u_SM} = T_{s_SM} + T_{wait} - T_{ack} \quad (C8)$$

The expected packet transmission delay is then given by:

$$T_{d_SM} = \left(\frac{P_{pSM}}{1 - P_{pSM}} \right) T_{u_SM} + T_{s_SM} \quad (C9)$$

where P_{pSM} are the packet error probability of the cooperative SM system which can be obtained from [15] for synchronous scenario and Appendix B for asynchronous scenario.

C. Cooperative Low Duty Cycle MIMO System

In addition to the delay incurred as calculated and analysed in previous subsection for $CMAC_{ON}$ with both BF and SM cooperative schemes, the cyclic RTS-CTS transmission scheme periods which are calculated in (1) are included. Also, the IFS periods for both RTS and CTS packet transmissions as calculated in (2) are included.

The transmission period of cooperative BF and SM data packets is the same as that for the SISO system due to the fact that the packet size and the modulation scheme are the same. The duration of a successful transmission attempt for BF scheme is given as:

$$T_{s_M} = (R \times T_{rs}) + (C \times T_{cts}) + (R - 1) \times (T_{ifs_rs}) + (C - 1) \times (T_{ifs_cts}) + T_{Bs} + T_{data} + T_{ack} \quad (C10)$$

and the period with an unsuccessful transmission attempt for BF scheme is given as:

$$T_{u_M} = T_{s_M} - T_{ack} + T_{wait} \quad (C11)$$

The expected packet transmission delay is then given by:

$$T_{d_M} = \left(\frac{P_{pBF}}{1 - P_{pBF}} \right) T_{u_M} + T_{s_M} \quad (C12)$$

where P_{pBF} is the packet error probability of the cooperative BF system which can be obtained from [15] for synchronous scenario and Appendix B for asynchronous scenario.

For the case of cooperative MIMO SM, we introduce the delay for the broadcast transmission time of a recruitment

message sent by the destination node, T_{Brand} the delay for the time required by the cooperating receiving nodes (N-1) to send the data to the destination, T_{col} . The duration of a successful transmission attempt for SM scheme is given as:

$$T_{s_SM} = T_{s_M} + T_{Br} + T_{col} \tag{C13}$$

and the period with an unsuccessful transmission attempt for SM scheme is given as:

$$T_{u_SM} = T_{s_SM} + T_{wait} - T_{ack} \tag{C14}$$

The expected packet transmission delay is then given by:

$$T_{d_SM} = \left(\frac{P_{pSM}}{1 - P_{pSM}} \right) T_{u_SM} + T_{s_SM} \tag{C15}$$

where P_{pSM} are the packet error probability of the cooperative SM system which can be obtained from [15] for synchronous scenario and Appendix B for asynchronous scenario.

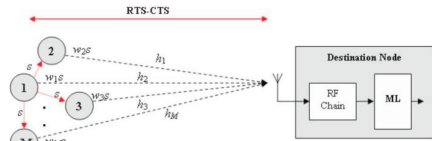


Fig. 1. A cooperative beamforming transmit diversity system with M transmit nodes and 1 destination.

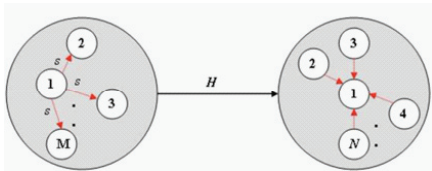


Fig. 2. A cooperative spatial multiplexing system with M transmit nodes and N receive nodes.

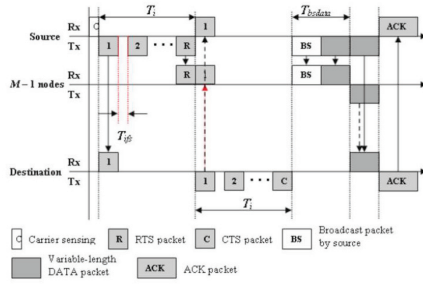


Fig. 3. Timing diagram of CMAC_{BF} cooperative transmission.

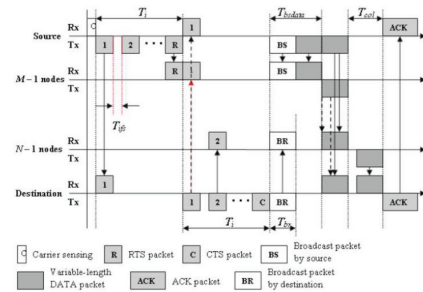


Fig. 4. Timing diagram of CMAC_{SM} cooperative transmission.

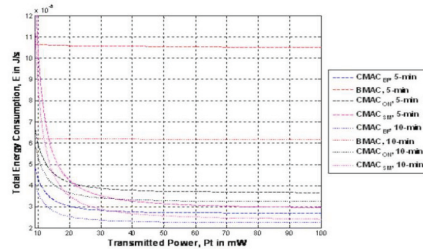


Fig. 5. Total energy consumption vs. transmission power of various MAC protocols with M = 2 and N = 1 (BF) and M = N = 2 (SM) for 5-min and 10-min sample periods.

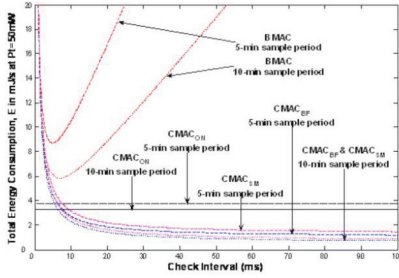


Fig. 6. Total energy consumption vs. check interval of various MAC protocols with $M = 2$ and $N = 1$ (BF) and $M = N = 2$ (SM) for 5-min and 10-min sample periods.

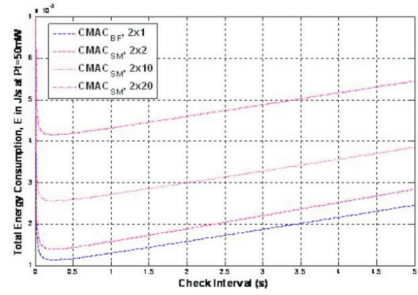


Fig. 9. Total energy consumption vs. check interval of CMAC protocols for various N (SM) with fixed $M = 2$ for all cooperative schemes.

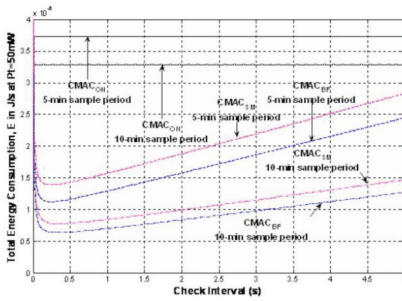


Fig. 7. Total energy consumption vs. check interval of CMAC protocols when $M = 2$ and $N = 1$ (BF) and $M = N = 2$ (SM) for 5-min and 10-min sample periods.

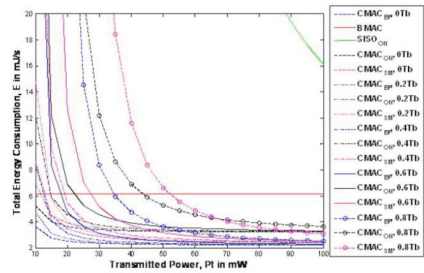


Fig. 10. Total energy consumption vs. transmission power for various asynchronous cooperative schemes with $M = 2$ and $N = 1$ (BF) and $M = N = 2$ (SM).

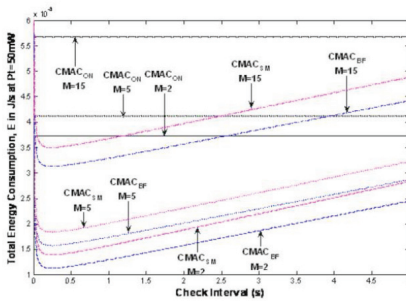


Fig. 8. Total energy consumption vs. check interval of CMAC protocols for various M with $N = 1$ (BF) and $N = 2$ (SM).

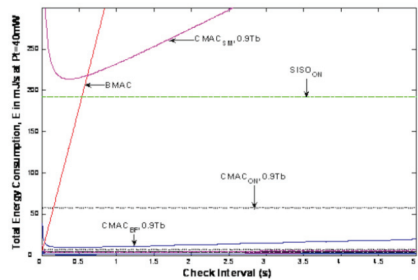


Fig. 11. Total energy consumption vs. check interval for various asynchronous cooperative schemes with $M = 2$ and $N = 1$ (BF) and $M = N = 2$ (SM) at clock jitter = $0.9T_b$.

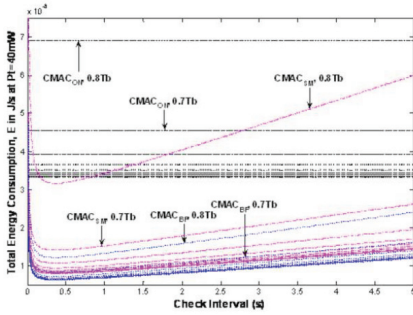


Fig. 12. Total energy consumption vs. check interval for various asynchronous schemes with $M = 2$ and $N = 1$ (BF) and $M = N = 2$ (SM) with clock jitter $\leq 0.8T_b$.

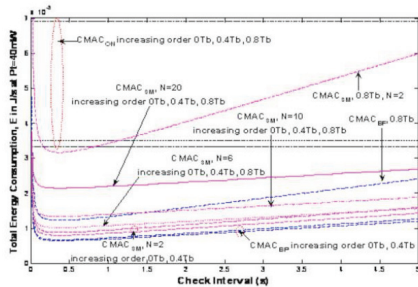


Fig. 13. Total energy consumption vs. check interval for various asynchronous schemes with $M = 2$ and $N = 1$ (BF) and with $M = 2$ and various $N = 2, 6, 10,$ and 20 (SM) with clock jitter $\leq 0.8T_b$.

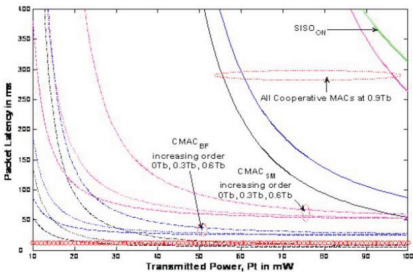


Fig. 14. Packet latency vs. transmission power of various asynchronous schemes with $M = 2$ and $N = 1$ (BF) and $M = N = 2$ (SM) for $0T_b, 0.3T_b, 0.6T_b$ and $0.9T_b$.

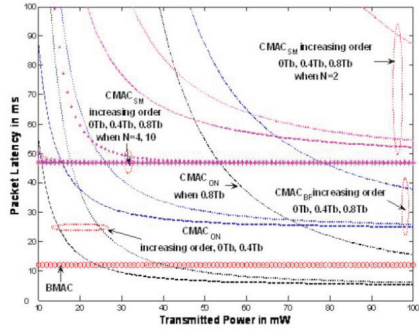


Fig. 15. Packet latency vs. transmission power of various asynchronous schemes with $M = 2$ and $N = 1$ (BF) and with $M = 2$ and various $N = 2, 4,$ and 10 (SM) for $0T_b, 0.4T_b$ and $0.8T_b$.

VI. REFERENCES

- R. Min and A. Chandrakasan. 2003. MobiCom Poster: Top Five Myths about the Energy Consumption of Wireless Communication, ACM SIGCOMM Mobile Computing and Communication Review, vol. 7, pp. 65-67.
- S. Cui, A. J. Goldsmith, and A. Bahai. 2004. Energy-efficient of MIMO and Cooperative MIMO Techniques in Sensor Networks, IEEE Journal on Selected Areas in Communications, vol. 22, issue 6, pp. 1089-1098.
- T.-D. Nguyen, O. Berder, and O. Sentieys. 2007. Cooperative MIMO Schemes Optimal Selection for Wireless Sensor Networks," IEEE Vehicular Technology Conference (VTC2007), Baltimore, MD, USA.
- W. Liu, X. Li, and M. Chen. 2005. Energy Efficiency of MIMO Transmissions in Wireless Sensor Networks with Diversity and Multiplexing Gains," IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2005), Philadelphia, USA.

- S. Jagannathan, H. Aghajan, and A. Goldsmith, 2004. The effect of time synchronization errors on the performance of cooperative MISO systems, IEEE Global Communications Conference (Globecom), Dallas, Texas, USA.
- X. Li. 2004. Space-Time Coded Multi-Transmission Among Distributed Transmitters Without Perfect Synchronization," IEEE Signal Processing Letters, vol. 11, pp. 948-951.
- X. Li, M. Chen, and W. Liu. 2004. Cooperative Transmissions in Wireless Sensor Networks with Imperfect Synchronization," Conference on Signals, Systems and Computers, Pacific Grove, CA.
- X. Li and J. Hwu. 2006. Performance of Cooperative Transmissions in Flat Fading Environment with Asynchronous Transmitters, Military Communications Conference (MILCOM 2006), Washington DC, USA.
- H. Yang, H.-Y. Shen, and B. Sikdar. 2007. A MAC Protocol for Cooperative MIMO Transmissions in Sensor Networks, IEEE Global Communications Conference, Exhibition and Industry Forum 2007 (GLOBECOM 2007), Washington DC, USA.
- M. Stemm and R. H. Katz. 1997. Measuring and Reducing Energy Consumption of Network Interfaces in Hand-held Devices," IEICE Transactions on Communications, vol. E80-B, pp. 1125 - 1131,
- S. Singh and Cauligi S. Raghavendra. 1998. Power-aware Multi-access protocol with signalling for ad-hoc networks, ACM Computer Communication Review, vol. 28, pp. 5-26.
- C. Guo, L. Zhong, and J. Rabaey, 2001. Low Power Distributed MAC for Ad-hoc Sensor Radio Networks, GLOBECOM, San Antonio, Texas, USA.
- X. Li. 2003. Energy Efficient Wireless Sensor Networks with Transmission Diversity," IET Electronics Letters, vol. 39, pp. 1753-1755,
- M. Dohler, Y. Li, B. Vucetic, A. H. Aghvami, M. Arndt, and D. Barthel. 2006. Performance Analysis of Distributed Space-Time Block-Encoded Sensor Networks, IEEE Transactions on Vehicular Technology, vol. 55, pp. 1776-1789.
- M. R. Ahmad, E. Dutkiewicz, and X. Huang. 2008. Performance Analysis of Cooperative MIMO Transmission Schemes in WSN, 19th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Cannes, France.
- J. Polastre, J. Hill, and D. Culler, 2004. Versatile Low Power Media Access for Wireless Sensor Networks, ACM Conference on Embedded Networked Sensor Systems (Sensys), Baltimore, Maryland, USA.
- M. Buettner, G. Yee, E. Anderson, and R. Han. 2006. X-MAC: A Short Preamble MAC Protocol for Duty-Cycled Wireless Sensor Networks, 4th ACM International Conference on Embedded Sensor Systems (Sensys).
- K. J. Wong and D. Arvind. 2006. SpeckMAC: Low Power Decentralized MAC Protocols

- for Low Data Rate Transmissions in Specknets," 2nd International Workshop on Multi-hop Ad-hoc Networks: From Theory to Reality, Florence, Italy.
- K. J. Wong and D. Arvind. 2007. A Hybrid Wakeup Signalling Mechanism for Periodic-Listening MAC Algorithms, ICON.
- M.R.Ahmad, E.Dutkiewicz, and X.Huang. 2008. Performance Evaluation of MAC Protocols for Cooperative MIMO Transmissions in Sensor Networks," 5th ACM Performance Evaluation Workshop on Ad-hoc, Sensor and Ubiquitous Networks (PE-WASUN2008), Vancouver, Canada,
- A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, and J. Anderson, 2002. Wireless Sensor Networks for Habitat Monitoring" ACM International Workshop on Wireless Sensor Networks and Applications.
- M. Kohvakka, M. Kuorilehto, M. Hannikainen, and T. D. Hamalainen, 2006. Performance Analysis of IEEE 802.15.4 and Zigbee for Large-Scale Wireless Sensor Network Applications," ACM International Workshop on Performance Evaluation of Wireless Ad hoc, Sensor, and Ubiquitous Networks Malaga, Spain.
- M. Kuorilehto, M. Kohvakka, J. Suhonen, P. Hamalainen, M. Hannikainen, and T. D. Hamalainen. 2007. Ultra-Low Energy Wireless Sensor Networks in Practice, First ed: John Wiley & Sons.
- J. G. Proakis. 2001. Digital Communications, Fourth ed. Singapore: McGraw-Hill.
- E. G. Larsson and P. Stoica. 2003. Space-Time Block Coding for Wireless Communications, First ed. Cambridge, UK: Cambridge University Press.