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MAC Protocols for Cooperative Diversity in Wireless Sensor Networks

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Abstract

Cooperative diversity has emerged as a promising technique to combat fading and improve reliability in a wireless environment. In cooperative diversity protocols, neighboring nodes act as virtual multiple-input-multiple-output (VMIMO) systems, where they cooperate with the transmitter-receiver pair to deliver multiple copies of a packet to the receiver via *spatially independent* fading channels. These multiple copies of the same packet can be combined at the receiver to recover the original packet. Medium Access Control (MAC) protocols play an important part in realizing this concept by effectively coordinating handshake and transmissions between source, partner and destination nodes. In this thesis, we investigate opportunities for improving reliability in Wireless Sensor Networks using cooperative MAC protocols.

First, a Medium Access Control protocol, called CPS-MAC, is proposed. This protocol uses overhearing to its advantage, which is considered an undesirable effect in conventional wireless systems. CPS-MAC intentionally wakes up neighbors to improve their chances of overhearing a packet. These packets are buffered and then relayed to the next hop neighbor where multiple copies of the same packet can be combined to increase the likelihood of recovering the original packet. Design challenges such as efficiently waking up neighborhood nodes, minimizing energy overhead, and partner selection are also addressed. Then, Reliable Cooperative Transmission-MAC (RCT-MAC) is proposed which extends the functionality of Cooperative Preamble Sampling-MAC (CPS-MAC) by implementing the *Cooperation on Demand* concept: nodes cooperate only when needed. Furthermore, RCT-MAC is one of the first attempts to compare the performance of a cooperative Wireless Sensor Network (WSN) MAC protocol against conventional protocols for WSNs namely B-MAC, L-MAC, and IEEE 802.15.4. The reliability vs energy efficiency tradeoff is analyzed for both CPS-MAC and RCT-MAC. Lastly, we evaluate a *Packet Error Prediction* scheme particularly envisioned for preamble sampling cooperative protocols and meant to supplement traditional partner selection schemes. The idea is to predict the chances of a partner node receiving an erroneous packet from the source based on the previously received preamble packets. The correlation between the handshake packets and data packets is analyzed using empirical data.

Zusammenfassung

Kooperative Diversität (cooperative diversity) hat sich als aussichtsreiche Technik zur Vermeidung von Signalstärkenverlust (fading) in kabellosen Netzwerken erwiesen. In kooperativen Diversitätsprotokollen agieren Nachbarknoten als virtuelle Mehrfach-Ein-Ausgabe-Systeme (virtual multiple-input-multiple-output, VMIMO), welche mit Sende-/Empfängerknoten kooperieren, um mehrfache Kopien eines Datenpakets zu übertragen. Dabei wird die übertragung von Daten zwischen zwei Knoten durch räumliche Diversität und mehrfachen Versand verbessert. Dies geschieht durch das Zusammensetzen der empfangenen Pakete beim Empfängerknoten zum ursprünglich verschickten Paket.

In einem solchen System sind Medienzugriffsprokolle (Medium Access Control, MAC) notwendig zur Koordination (handshake) und Datentransport zwischen Quell-, Partner- und Zielknoten. In dieser Arbeit untersuchen wir die Verbesserung der Zuverlässigkeit von drahtlosen Sensornetzen mit Hilfe von kooperativen MAC-Protokollen.

Zunächst stellen wir ein Medienzugriffs-Kontrollprokoll names *CPS-MAC* vor. Dieses Protokoll nutzt die Fähigkeit eigentlich unbeteiligter Knoten, Datenpakete mitlesen zu können (overhearing), welches in konventionellen drahtlosen Netzwerken unerwünscht ist, zu seinem Vorteil. Dazu weckt CPS-MAC Nachbarknoten auf, um die Wahrscheinlichkeit, ein Paket mitzulesen, zu erhöhen. Diese Pakete werden zwischengespeichert, um daraufhin zum nächsten Knoten weitergeleitet zu werden. Der Empfänger setzt nun die erhaltenen (Mehrfach-)Kopien der Pakete zu einem Datensatz zusammen; der mehrfache Versand erhöht die Wahrscheinlichkeit, daß alle Pakete korrekt zum Empfänger geleitet wurden und das Datum erfolgreich zusammengesetzt werden kann. Das effiziente *Aufwecken* von Nachbarknoten wird hierbei ebenso adressiert wie die Minimierung das Stromverbrauchs und die korrekte Selektion eines Nachbarknotens innerhalb des Netzwerkes. Im nächsten Schritt stellen wir RCT-MAC (Reliable Cooperative Transmission-MAC) vor, welches die Funktionalität von CPS-MAC um Kooperation von Netzwerkknoten im Bedarfsfall (Cooperation on Demand) erweitert. Wir vergleichen RCT-MAC mit konventionellen, nicht-kooperativen Protokollen wie B-MAC, L-MAC und IEEE 802.15.4. Zudem untersuchen wir den Abtausch von Zuverlässigkeit und Energieeffizienz. Schließlich untersuchen wir Methoden zur Vorhersage von Fehlern in der Datenübertragung (Packet Error Prediction) zur Verbesserung der Wahl eines Kommunikationspartners im Rahmen des *preamble samplings*. Hierbei wird die Rate von fehlerhaften Präambeln als Maßstab für die Güte des übertragungswegs zwischen Quell- und Partnerknoten herangezogen. Die Korrelation zwischen *Handshake-Paketen* (Präambel) und Datenpaketen wird anhand von empirischen Daten analysiert.

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Abbreviations

ACK	Acknowledgment
AP	Access Point
ARP	Address Resolution Protocol
ARQ	Automatic Request Repeat
CW	contention window
CC	Cooperative Communication
CD	Cooperative Diversity
CDMA	Code Division Multiple Access
CPS-MAC	Cooperative Preamble Sampling-MAC
CRC	Cyclic Redundancy Check
CSI	Channel State Information
CSMA-CA	Carrier Sense Multiple Access scheme with Collision Avoidance
CTS	Clear To Send
DCF	Distributed Coordination Function
DIFS	Distributed Inter-Frame Space
EPUB	Energy per Useful Bit
FDMA	Frequency-Division Multiple Access
HC	Hop Count
LPL	Low Power listening
LQI	Link Quality Indication
MAC	Medium Access Control
MPS	Minimum Preamble Sampling
MRC	Maximum Ratio Combining
NACK	Negative Acknowledgment
OMNeT++	OMNeT++ Network Simulator
PCF	Point Coordination Function

PER	Packet Error Rate
PDR	Packet Delivery Ratio
RCT-MAC	Reliable Cooperative Transmission-MAC
RSSI	Received Signal Strength Indication
RTS	Request To Send
SIFS	Short Inter-Frame Space
SNR	Signal-to-Noise Ratio
SYNC	Synchronization
TDMA	Time Division Multiple Access
VMIMO	Virtual Multiple-Input-Multiple-Output
WLAN	Wireless LAN
WSN	Wireless Sensor Network

List of Publications

- R. A. M. Khan and H. Karl, MAC Protocols for Cooperative Diversity in Wireless LANs and Wireless Sensor Networks, IEEE Communications Surveys & Tutorials, vol.16, no.1, pp. 46-63, 2013.
- R. A. M. Khan and H. Karl, Simulating Cooperative Diversity Protocols for Multihop Wireless and Sensor Networks, 11th. GI/ITG KuVS Fachgespräch Wireless Sensor Networks (FGSN), 2012.
- R. A. M. Khan and H. Karl, Multihop Performance of Cooperative Preamble Sampling MAC (CPS-MAC) in Wireless Sensor Networks, 10th International Conference on Ad Hoc Networks and Wireless (ADHOC-NOW), pp. 145-149, 2011.
- R. A. M. Khan and H. Karl, Cooperative Communication to Improve Reliability and Efficient Neighborhood Wakeup in Wireless Sensor Networks, Fourth International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies (UBICOMM), pp. 334-341, 2010.

Chapter 1

Introduction

Wireless Sensor Networks (WSNs) are used in a wide range of applications, such as target tracking, habitat sensing and fire detection. WSNs are particularly useful in situations where an infrastructure network is not present or not feasible. In such conditions, sensor nodes can be deployed around a sink to create a multi-hop data gathering network as shown in Figure 1.1. The nodes coordinate locally to forward each others' packets. The packets travel in a hop-by-hop fashion towards the sink.

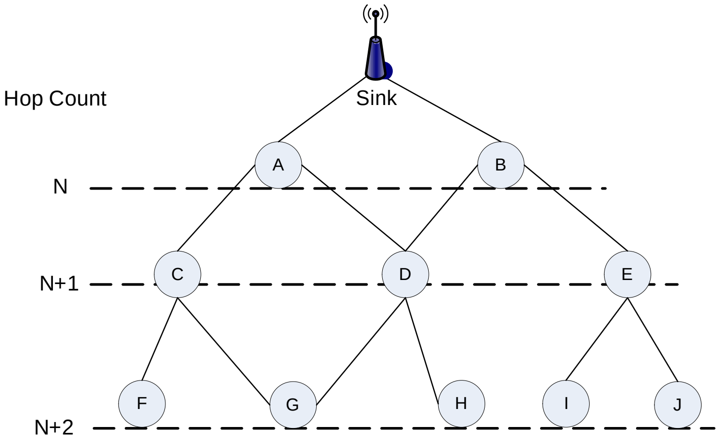

Figure 1.1: Data gathering network

As sensor nodes are usually battery-powered, they operate under strict energy constraints. Therefore, common WSN protocols such as S-MAC, T-MAC and CSMA-MPS are designed to maximize energy efficiency [2, 3]. The nodes use low transmission power and switch the transceiver between sleep and awake states.

The broadcast nature of the wireless channel, especially in urban areas, results in signal interference and collisions among simultaneous senders due to which these networks drop a significant proportion of packets. Another undesirable effect is overhearing in contention-based protocols where all the awake nodes in the transmission range of a sender receive packets transmitted by the sender even though only one of them is the intended receiver. These overheard packets are discarded, which negatively affects the energy efficiency. Furthermore, mobile deployment leads to problems such as fading.

Signal fading can be the most severe among these impairments. In a wireless channel, random scattering from reflectors results in multiple copies of a transmitted signal arriving (and interfering) at a receiver with different channel gains, phase shifts, and delays. These multiple signal replicas can add together in a constructive or destructive way, amplifying or attenuating the received signal's amplitude. Destructive interference results in fading, which causes temporary failure of communication, as the amplitude of the received signal may be low to the extent that the receiver may not be able to distinguish it from thermal noise.

Under such conditions, ensuring reliable communication while conserving energy is a challenging problem. Traditional approaches such as Automatic Request Repeat (ARQ) rely on retransmitting a packet once a failed transmission is detected via lack of Acknowledgment (ACK) using timeouts or explicit negative ACK. This thesis investigates an alternative approach for improving reliability in energy-constrained WSNs using Cooperative Diversity. First, Cooperative Diversity and MAC protocols are introduced in the Section 1.1 and 1.2, respectively. Then, motivation and contribution is discussed in Section 1.3.

1.1 Cooperative Diverstiy

Cooperative diversity[1] has emerged as a promising technique for improving reliability in a wireless environment. Conventional wireless systems are designed in such a way that any single transmission involves only two nodes, a transmitter and a receiver. The receiver could possibly be the ultimate destination or just an intermediate node in a larger multi-hop network. In cooperative diversity, on the other hand, additional node(s) cooperate with the transmitter-receiver pair to deliver multiple copies of a packet to the receiver via independently fading channels. This is interesting because a transmission in

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[1] Also referred to as cooperative communication. Common usage has resulted in the two terms being used interchangeably and are used in the same context in this thesis.

a wireless channel is overheard by neighboring nodes anyway, but discarded in conventional systems. These neighboring nodes can be employed for cooperation as relay(s) to retransmit a (possibly processed) copy of the overheard packet to the receiver. The destination can *combine* these packets, received from the source and relay(s), thereby exploiting spatial diversity to recover a packet which might have unnecessarily been discarded in conventional communication. This reduces end-to-end propagation loss, provides robustness against channel variations due to fading, and improves coverage. For packet combining, diversity combining techniques such as selection combining or maximal ratio combining can be used [4]. Wireless systems that use cooperative diversity are also known as virtual multiple-input-multiple-output (VMIMO) systems [5].

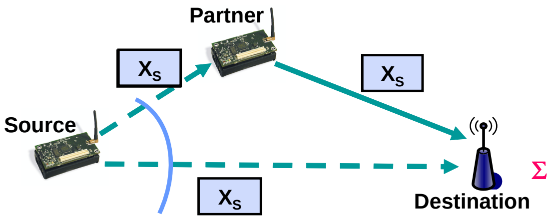


FIGURE 1.2: Cooperative Diversity Scenario

Figure 1.2 illustrates a simple cooperative diversity transmission. In the first phase, a source broadcasts a message X_s, represented by the dotted line, to a destination which is overheard by a neighboring partner. In the second phase, the neighboring partner forwards the message X_s, received in the first phase, to the destination. The two packets can be combined, denoted by $\sum$, at the destination to recover the transmitted data. Such cooperative transmissions are envisioned for integration in larger networks where multiple relay nodes are available and protocols exist for selecting the relay which optimizes one or more of the desired metrics, e.g., battery life, best source-relay-destination channel. Relay selection is an important research topic in cooperative diversity systems, and researchers have recently focused on developing distributed solutions for relay selection [6–8]. Classification and analysis of relay selection protocols can be found in [9–11].

The development of cooperative diversity protocols has received significant attention from the research community during the last decade. These protocols optimize various cooperative functions such as how forwarding decisions are taken by partner nodes in the second phase and how nodes schedule packet transmissions to increase throughput or reduce energy consumption. We introduce both of these aspects in the following section. This was also presented by us, previously, in reference [11].

1.1.1 Cooperative Diversity Protocols

Laneman et al. coined the term cooperative diversity and introduced the following categories of diversity protocols [12, 13].

1.1.1.1 Static Protocols

In static protocols, the transmission from the source and the partner follows a fixed pattern in which the source transmits a packet in the first phase and the partner repeats the received packet in the second phase. This scheme is attractive because of its simplicity and ease of implementation; however, it suffers from drawbacks due to its repetition-coding nature. Firstly, if the destination receives the packet correctly in the first phase, it makes the second phase redundant. Secondly, if reception at the partner fails in the first phase, the second phase is wasted.

To counter these limitations in static protocols, adaptive protocols were proposed that include selection relaying and incremental relaying, which is introduced in the next section [13].

1.1.1.2 Adaptive Protocols

1. *Selection Relaying*

   In selection relaying, if the transmission from the source to the partner fails in the first phase, the partner idles and the source itself instead retransmits a copy of the original message directly to the destination in the second phase [13]. This prevents wasting of the second phase if the source-partner transmission fails in the first phase. This protocol assumes that a partner is selected before the first phase and therefore cannot be changed at the start of the second phase.

2. *Incremental Relaying*

   In incremental relaying, it is assumed that the destination is able to give feedback to the source and the partner nodes after each transmission. So if a transmission from the source to the destination was successful in the first phase, the partner might not need to retransmit the packet, thereby eliminating the need for a second phase. This protocol was shown to have the best performance among the proposed protocols in terms of spectral efficiency [13].

Further work introduced the idea of user cooperation [14, 15]. The idea is to couple two users for cooperation so that each of the users is responsible for transmitting its own as well as its partner's information.

1.1.2 Forwarding Decision

The protocols introduced in the previous section define the packet scheduling behavior of the source, partner, and destination nodes. The partner node, after receiving the packet from the source, can additionally process the packet and make a forwarding decision based on the outcome of the criteria defined in the protocol. In this section, we introduce some existing protocols used by partner nodes for making forwarding decisions.

1.1.2.1 Amplify and Forward

In amplify and forward, a partner simply amplifies the received signal and forwards it to the destination [16, 17]. This scheme is non-regenerative, which means that no decoding and re-encoding is performed on the received signal at the partner node. This scheme appears to be simple, but sampling, amplifying, and retransmitting analog values is not a technologically trivial matter. Another drawback is that due to its non-regenerative nature, any noise received with the signals is also amplified and retransmitted, which can affect the overall performance of the system.

1.1.2.2 Decode and Forward

In decode and forward, a partner node extracts symbols from the received signal and demodulates them to bits [16, 17]. These bits can be checked for errors, for example, by using a cyclic redundancy check (CRC) and the result used by the partner for making forwarding decisions. An erroneous packet may be dropped to prevent propagation of errors. Correctly received packets are encoded again and retransmitted to the destination.

1.1.2.3 Compress and Forward

In compress and forward, instead of simply repeating the symbols in the second phase, the relay compresses the symbols and includes them in the relayed packet to reduce redundancy. Specifically, the relay quantizes the received signal from the source, encodes the samples into a new packet, and forwards it to the destination [18]. Although compressing data can be computationally expensive for the partner, the destination will need to decompress data received in the second phase only when the direct transmission failed in the first phase.

1.2 Medium Access Control

Medium Access Control (MAC), in combination with logical link control, comprises the data link layer of the OSI model. The data link layer is responsible for the following functions [19].

1. Converts packets to frames.
2. Encapsulates and decapsulates frames.
3. Ensures reliability using acknowledgments and retransmission.
4. Prevents a receiver's buffer from overflowing (flow control).
5. Performs error checking on frames to prevent errors from propagating to higher layers.
6. Controls access to the medium via the Medium Access Control (MAC) sublayer. MAC is responsible for
   (a) Coordinating channel access among multiple nodes as per requirements of the application scenario, e.g., fair share of access to medium or optimal channel utilization [19].
   (b) Minimizing collisions by preventing nodes, which can interfere with other transmissions, from transmitting simultaneously.
   (c) Effectively duty-cycling the radio to conserve energy in WSNs.

In Figure 1.3, we represent a hierarchical organization of MAC protocols for WLAN and WSN [11]. A brief introduction to MAC protocols for WLAN and WSN is presented in Section 1.2.1 and Section 1.2.2, respectively.

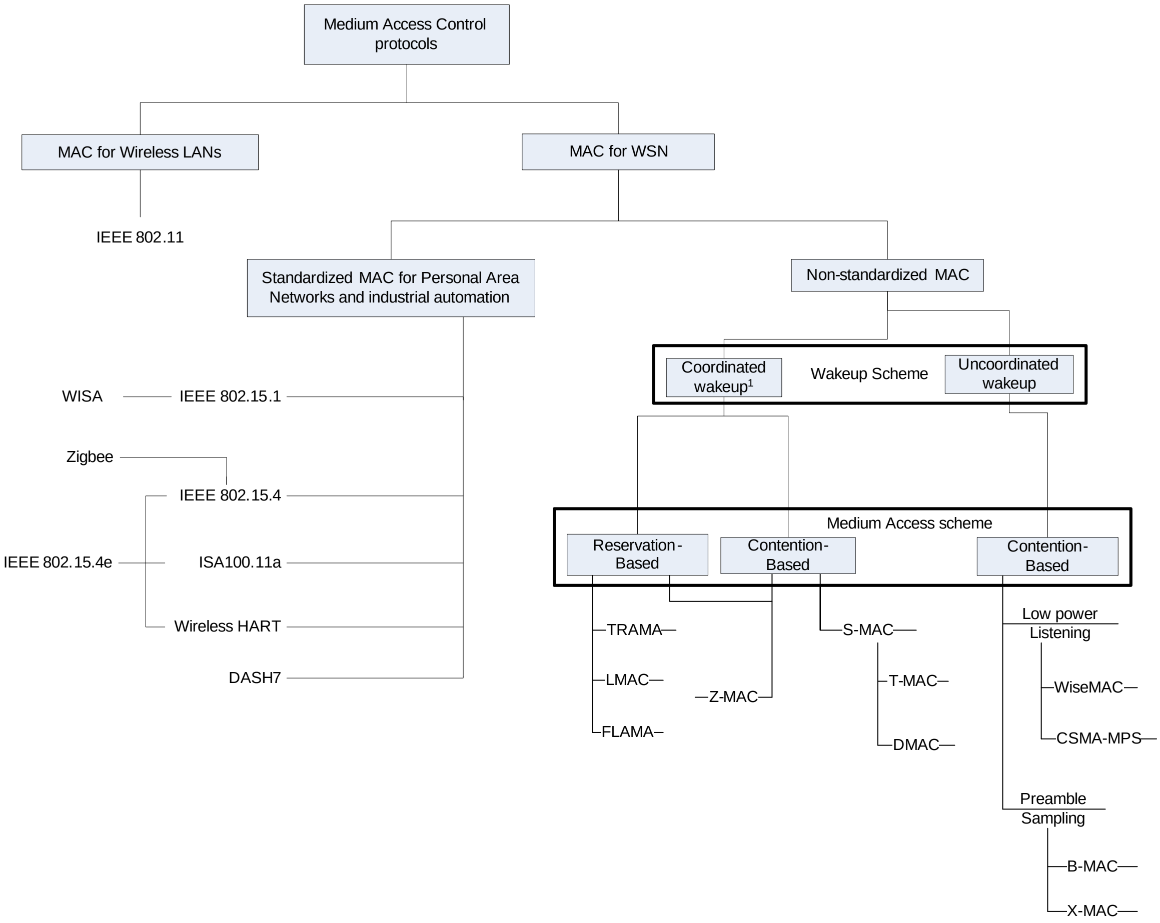


FIGURE 1.3: MAC protocols for WLAN and WSN

1.2.1 Medium Access Control in Wireless LAN

Wireless LANs (WLANs) were ratified by the Institute of Electrical and Electronics Engineers (IEEE) as the IEEE 802.11 standard [20]. Most modern WLANs use an enhanced version of IEEE 802.11 providing high data rates, namely IEE 802.11a, 802.11g, 802.11n, or 802.11ac.

The IEEE 802.11 MAC defines two transmission modes for data packets, a contention-free mode called Point Coordination Function (PCF) and a contention-based mode called Distributed Coordination Function (DCF). A brief introduction to DCF and PCF is presented below. Our study shows that cooperative protocols do not use the PCF mode. DCF, on the other hand, is widely used in cooperative protocols.

1.2.1.1 The Distributed Coordination Function (DCF)

The basic access mechanism, called the Distributed Coordination Function, is a Carrier Sense Multiple Access scheme with Collision Avoidance (CSMA/CA), where a station is allowed to initiate a data transmission if it senses that the medium is idle (i.e., no other station is transmitting). Request To Send (RTS) and Clear To Send (CTS) control frames are used to reserve channel time and prevent neighboring nodes from simultaneously transmitting, as shown in Figure 1.4. Here, DIFS (Distributed Inter-Frame Space) and SIFS (Short Inter-Frame Space) are used for frame spacing. Frame spacing allows assigning priorities to a transmission based on its type (control or data frame). The control frames (RTS/CTS) include the source node address, destination node address, and a Network Allocation Vector (NAV) that specifies the duration of time that the medium will be busy.

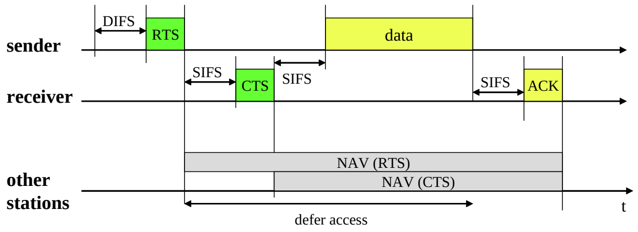


FIGURE 1.4: Distributed Coordination Function

We observe in this thesis that DCF is the most commonly used MAC scheme based on which cooperative MAC protocols are developed, as discussed in Section 2.1 and 2.2.

1.2.1.2 Point Coordination Function (PCF)

To support time-bounded services, the IEEE 802.11 standard also defines the optional Point Coordination Function (PCF). PCF allows contention-free access to nodes in a wireless medium, coordinated by a Point Coordinator (PC), which is typically located within the Access Point (AP). Under PCF, time is divided into repeated periods, called superframes, where each superframe is composed of a Contention-Free Period (CFP) and a subsequent Contention Period (CP). During a CFP, PCF is used for accessing the medium, while DCF is used during a CP. This allows nodes with or without time-bounded transmission requirements to communicate with the AP. PCF mode is optional and our study shows that it is not commonly utilized for cooperative communication protocols.

More details on DCF and PCF can be found in reference [20].

1.2.2 Medium Access Control in Wireless Sensor Networks

In WSN, battery-powered sensor nodes try to conserve energy by duty-cycling their transceivers, i.e., by switching the transceiver between the sleep and the awake state. Development of MAC protocols for such energy-efficient behavior has received significant interest from the research community. A recent survey lists close to 75 MAC protocols for WSN, with the count still increasing [21]. To assist engineers and scientists interested in investigating this literature, it is important to categorize these MAC protocols on the basis of their design objective. A previous categorization [2] is available which uses the multiplexing scheme, meaning how multiple nodes access the media. Such a categorization would not give an overview of how nodes schedule their duty cycles and the corresponding rendezvous problem. A recent survey takes this into account and presents a more comprehensive tabular categorization of MAC protocols for WSNs [21]. However, standardized protocols for WSN have not been considered in either of the previous categorizations. We present a new hierarchical organization of these protocols in Figure 1.3 and divide the protocols into two main categories, standardized and non-standardized. A brief introduction to both of these categories is presented below [11].

1.2.2.1 Standardized MAC Protocols

The need for WSN in industrial automation has motivated the development of various standards such as IEEE 802.15.4, wireless HART, ZigBee, DASH7, etc., as shown in Figure 1.3. Several large enterprises have formed the Wireless Industrial Technology Konsortium (WiTECK) for developing, promoting and distributing one or more communication stacks on a non-profit basis [22]. The idea is to encourage the use of these stacks on a standardized basis within the process control and factory automation markets. Currently, efforts are underway to enable compatibility between devices running these standard protocols, such as the IEEE 802.15.4e standard which is aimed at adding and enhancing functionality to the IEEE 802.15.4 standard to make it compatible with Wireless HART and ISA100.11a.

We present a brief introduction of the IEEE 802.15.4 protocol next as it is used for performance evaluation against our proposed protocol in Chapter 4. A detailed survey of protocols for industrial automation is presented in reference [23].

The *IEEE 802.15.4 MAC* protocol operates in the ISM frequency bands and defines two different types of devices: a full-function device (FFD) and a reduced-function device (RDD). An FFD can serve as a coordinator or a node. An RFD can only talk to an FFD node. The standard supports both star and peer-to-peer network topologies. In the star network, the communication occurs only between devices and a single central controller, called the personal area network (PAN) coordinator, which manages the whole PAN. In a peer-to-peer topology a PAN coordinator is present; however, any device can communicate with any other one as long as they are in range of one another.

IEEE 802.15.4 offers two kinds of medium access modes: unslotted and slotted. In unslotted mode, nodes contend for the media using CSMA/CA. In slotted mode, also called the beacon-enabled mode, a superframe structure is used. A superframe is bounded by periodically transmitting beacon frames, which allow nodes to associate with and synchronize to their coordinators. The superframe consists of two parts, an active and inactive period. An active period is divided into 16 consecutive time slots that form the beacon, contention access period (CAP), and contention-free period (CFP). In CAP, all nodes wanting to transmit must first contend for the medium and data transmission follows a successful execution of the slotted CSMA-CA algorithm. In CFP, a device can communicate with the PAN coordinator directly in slots called guaranteed time slots (GTS) without contending for the channel using a CSMA-CA mechanism. The GTSs are allocated by the PAN coordinator, therefore GTS transfer mode is only applicable in the star topology [24].

Attempts to use cooperation in these standardized protocols have been limited so far. References [25] and [26] use the IEEE 802.15.4 standard for cooperation and will be discussed in detail in Section 2.2. Some other related work [27] focuses on frequency diversity for ISA100.11a. Reference [28] includes cooperative distance classification for IEEE 802.15.4 networks. We consider these standardized protocols to be an important candidate for the future research and development of cooperative protocols.

1.2.2.2 Non-standardized MAC Protocols

Diverse application scenarios in WSN, each with unique communication, energy-efficiency and processing requirements, have motivated the academic community to aggressively research WSN protocols, which has resulted in a vast amount of literature on MAC and routing protocols [29]. We refer to these protocols as non-standardized protocols, as shown in Figure 1.3. We sub-categorize these protocols based on their wakeup scheme and their medium access scheme.

Wakeup Schemes The wakeup of nodes in WSN can be coordinated or uncoordinated.

1. *Coordinated Wakeup*

   The coordinated wakeup approach requires nodes to synchronize at some common time of reference such that they can wake up collectively or in a smaller preselected cluster configuration. For this purpose, neighboring nodes can exchange sleep schedules using control packets or beacons. However, this need to synchronize sleeping schedules and the corresponding control packet overhead make their implementation challenging, especially for large ad hoc networks. Optimally, a MAC protocol in a WSN should not impose a high overhead for exchanging control information. Otherwise, a significant amount of energy will be consumed for it.

   Protocols such as S-MAC and its descendant T-MAC are examples of such coordinated wakeup [30, 31]. In S-MAC , each node duty cycles the radio, as shown in Figure 1.5. This sleep and awake duration can be selected based on application requirements. In order to synchronize nodes for communication and prevent clock drift, neighboring nodes form a virtual cluster by exchanging sleep schedules, using synchronization packets, with neighboring nodes. Any node that is on the border of two virtual clusters follows the sleep schedule of both clusters for inter-cluster communication. Once the nodes in the virtual cluster wake up, they must contend within their own cluster for channel access. This is done using the RTS/CTS scheme described previously.

2. *Uncoordinated wakeup*

   Uncoordinated schemes, on the other hand, do not require synchronization of sleep schedules and are more flexible regarding sleep cycles [29]. One such popular scheme is preamble sampling, which is particularly useful when the traffic generation is aperiodic [32]. Protocols such as X-MAC and CSMA-MPS use such a wakeup scheme [3, 33]. Figure 1.6 shows the working of a preamble sampling protocol.

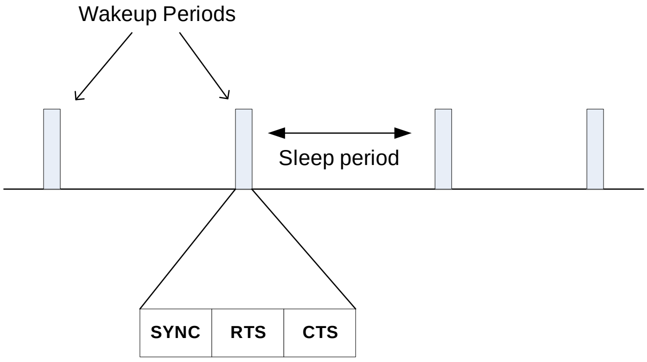


FIGURE 1.5: Duty Cycling. During the wakeup period node can send control packets (sync, RTS, CTS, etc) or data packets, if needed

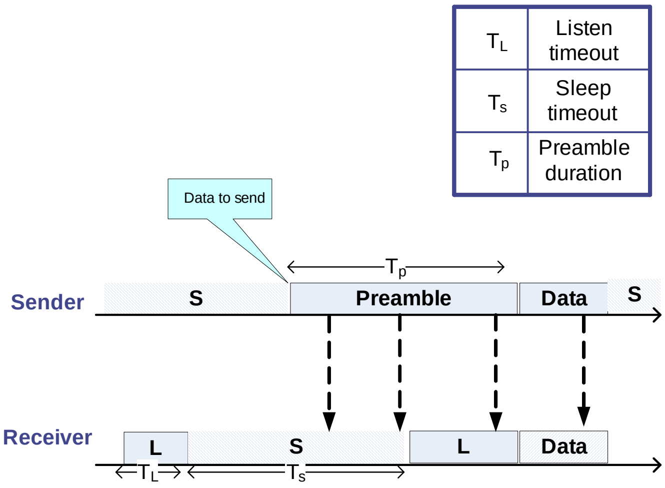


FIGURE 1.6: Preamble sampling

Nodes switch between sleep and listen (awake) states. When a sender has data to send, it wakes up the receiver by sending one long preamble of duration T_p, which is longer than the sleep duration T_s of the receiver node. Alternatively, one long preamble can be divided into a series of short preambles interleaved with listening intervals [3, 33]. When a receiver node wakes up and switches its radio to listen state, it hears the preamble, uses it to synchronize with the source, and stays awake for an incoming transmission. Then, the source initiates the transmission at the end of the preamble. After the transmission is complete, nodes resume duty cycling. It is important to note here that the price of waking up nodes, in terms of energy, is paid by the source i.e., nodes will only use additional energy for waking up neighbors when they have something to send.

To shorten the preamble length and further reduce energy consumption at both sender and receiver, an improvement to Preamble Sampling was proposed [3, 33].

This scheme is known as Minimum Preamble Sampling (MPS) and is shown in Figure 1.7.

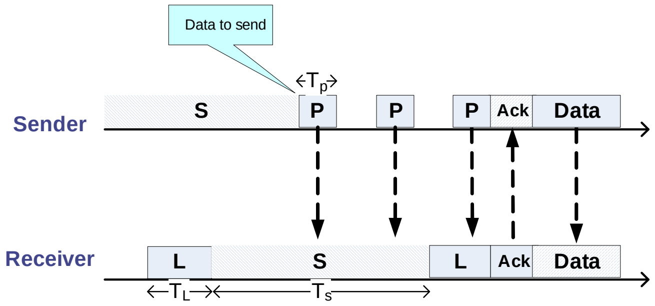


FIGURE 1.7: Minimum Preamble Sampling

Here, one long preamble is divided into a series of short preambles interleaved with listening intervals during which the sender of the preamble listens for a reply from the receiving node. We refer to these listening intervals as inter-preamble spacing. If a receiving node wakes up and hears the short preamble, it sends an ACK packet to the sender during the inter-preamble spacing. Upon receiving the ACK, the sender initiates the data transmissions.

Non-standardized Medium Access Schemes MAC schemes coordinate node access to the wireless channel and are well known from the wireless communications literature [4, 29]. Medium access can be reservation/assignment-based, contention-based, or hybrid i.e., a combination of the two.

1. *Reservation/Assignment-based scheme*

   In reservation/assignment-based schemes, typically a node acting as the coordinator or cluster head allocates time slots to nodes. This can be based on some predefined allotment or demand-based, where a node can request a time slot. This can possibly require exchange of control packets among the nodes and the coordinator before a slot can be assigned. This approach is attractive at first glance because it eliminates collision of data packets, reduces contention, and provides guarantees on channel access time. However, the need for a central coordinator, clock synchronization, control packet overhead, and implementation complexity on sensor nodes can make its implementation challenging. LMAC, TRAMA and FLAMA are examples for the Reservation/Assignment-based scheme. We present a brief introduction of LMAC next as it is used for performance evaluation against our proposed protocol in Chapter 4.

LMAC is a schedule-based MAC protocol which means time is organized into time slots which are then grouped into frames [34]. The number of frames in schedule-based protocols depends upon traffic load, network node density, or other communication requirements. As synchronization is needed for schedule-based schemes, this is done in LMAC using control messages. The control messages also allow the node to determine a local two-hop view of the network. When a node transmits a packet, it includes a bit vector containing information on slots occupied by itself and its neighbors. Neighboring nodes, upon receiving this message, mark the indicated time slots as occupied. If the receiving node has not yet reserved a time slot itself, it uses the gathered information to select a free time slot and transmits a message in that time slot. Meanwhile, it listens to other time slots and accepts data from neighboring nodes. This way nodes keeps receiving control information from neighboring nodes and update their neighborhood information accordingly.

Collisions in LMAC are possible when two or more nodes choose the same time slot for control message transmission, simultaneously. The nodes that caused the collision would not be able to detect the collision in a wireless environment because the transceiver would be in transmit mode. However, any neighboring node(s) that detect the collision will use their own time slot to inform the network that they detected a collision in the particular slot. When a node is informed that its transmission resulted in a collision in that slot, it gives up the time slot and begins the process of selecting a new timeslot [35].

2. *Contention-based schemes*

   These schemes are also known as random access schemes. Here, nodes that wish to transmit must contend for the channel and the winner transmits at the risk of collision. Accordingly, these protocols typically contain mechanisms, such as carrier sensing prior to transmission, to avoid or reduce the probability of collisions. If a station detects a collision through carrier sensing or through absence of a positive acknowledgment from its destination, it can possibly initiate a retransmission after waiting a random amount of time to prevent another collision. The previously discussed DIFS scheme (Figure 1.4) is an example of a contention-based scheme where RTS/CTS packets are used to reserve the medium. BMAC is also an example of a contention-based scheme. We present a brief introduction of

BMAC next as it is used for performance evaluation against our proposed protocol in Chapter 4.

BMAC is a preamble-sampling protocol. Figure 1.8 shows the working of BMAC. Nodes switch between sleep and listen (awake) states. When a sender has data to send, it wakes up the receiver by sending a series of short preambles. The duration from the start of the first preamble transmission until the end of the last preamble transmission must be longer than the sleep duration of the receiver node. This increases the likelihood of the receiver receiving at least one preamble during the listen state. After the preambles are sent, the sender sends the data packet which is acknowledged by the destination [19].

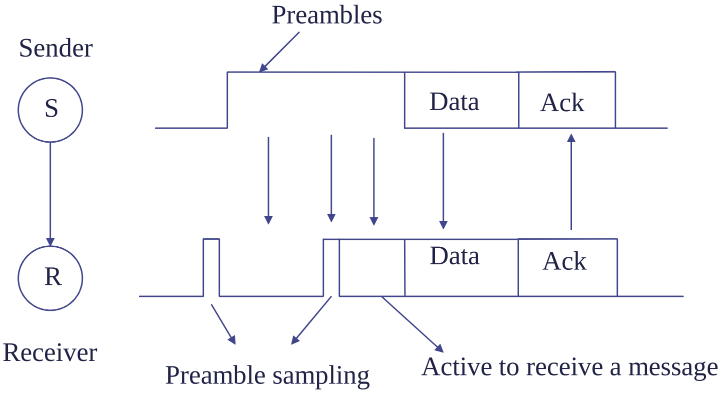


FIGURE 1.8: BMAC

Contention-based protocols are typically easier to implement than reservation/assignment-based schemes and require fewer control message exchanges. However, they considerably limit the throughput of the channel and might not be feasible for applications requiring time-bounded services.

3. *Hybrid Schemes*
   Hybrid MAC protocols such as Z-MAC [36] combine both a contention-based scheme and a reservation-based scheme. The idea is that a protocol should be able to respond to a varying traffic load and corresponding contention level in the network. For example, under low traffic load Z-MAC behaves like a contention-based CSMA scheme, and under high contention it behaves like a reservation-based scheme.

For readers interested in a comprehensive survey of MAC protocols for WSN, we suggest [2, 21] for non-standardized protocols and [23] for standardized protocols.

1.3 Thesis Motivation and Contributions

Most of the initial work in developing cooperative protocols was focused on physical layer schemes [12, 13, 15, 37]. Later, researchers also investigated the support of cooperative communication in higher protocol layers, particularly the MAC layer. This is because, in order to realize the full potential of cooperative communication, it is imperative that the MAC layer must schedule transmissions effectively and efficiently. The initial attention was focused on developing cooperative MAC protocols for WLAN based on the IEEE 802.11 standard [20, 38–41], discussed in Section 2.1.

In this thesis, we extend this idea to WSN and investigate how cooperative diversity can help in maintaining connectivity under non-reliable and fading conditions in WSNs. We approach the problem from a MAC layer perspective and use existing physical layer schemes to support our protocols. We are motivated by the following limitations in existing protocols and present two new cooperative MAC protocols for WSNs, namely CPS-MAC and RCT-MAC, discussed in Chapters 3 and 4, respectively.

1. Most cooperative protocols for WSN use the IEEE 802.11 DCF mode for handshaking and inter-frame spacing instead of the MAC protocols for WSN, shown in Figure 1.3. Scaling IEEE 802.11 DCF for WSNs may not be feasible because of strict energy constraints and limited processing power. We develop our MAC protocols on the preamble sampling concept, which is a native, non-cooperative WSN scheme [33, 42].

2. Cooperative diversity protocols require additional signaling and transmission, which consumes energy and makes their implementation in battery-powered WSN a challenging problem. While the energy utilization tradeoff of cooperative protocols has been researched from an information-theory and physical-layer perspective, analyzing this tradeoff for MAC protocols in WSN has not received attention. We focus our analysis on the cost of using cooperation in terms of energy consumption vs. reliability in WSN. This allows us to identify the price that cooperative protocols have to pay in terms of energy compared to non-cooperative protocols.

3. As the wireless channel is a shared medium, a larger network also means more interference, contention, and collisions. As WSNs can be densely deployed in an ad hoc fashion and data must hop over multiple nodes before reaching the destination, performance of a cooperative protocol can possibly degrade in such an environment due to additional signaling and transmission overhead. In our literature survey, we noticed a lack of performance analysis of cooperative MAC protocols in a multi-hop environment. Therefore, we extend CPS-MAC to dynamically change roles between source, partner, and destination nodes based on data flow and test its performance in a multi-hop network configuration where all nodes generate data. The results show that protocol performance is affected by the network size and traffic load.

4. Cooperative MAC protocols are diverse in nature. Most of the proposed protocols have been compared to a non-standard and non-cooperative protocol under different sets of metrics and scales. Furthermore, currently there is no benchmark available with which to compare these protocols. This limits the ability of an interested reader to evaluate these protocols against each other. We compare our RCT-MAC against well known MAC protocols for WSN namely IEEE 802.15.4, BMAC, and LMAC. We evaluate these protocols under different traffic scenarios, which gives a deeper insight into the benefits of using cooperative protocols over traditional WSN protocols.

5. In WSN protocols, nodes duty cycle their transceiver between sleep and awake state to conserve energy. An effective cooperative MAC protocol in WSN should incorporate a mechanism to wake up nodes prior to transmission. To the best of our knowledge, CPS-MAC proposed in Chapter 3 was one of the first attempts of its kind to incorporate such a wakeup mechanism.

1.4 Organization of the Thesis

The rest of the thesis is organized as follows. We present a literature review of existing Cooperative MAC protocols for WLAN and WSN in Chapter 2. In Chapter 3 we introduce Cooperative Preamble Sampling MAC (CPS-MAC) and show how cooperation can be integrated into WSN protocols with benefits in terms of reliability and energy utilization. Chapter 4 introduces RCT-MAC, which enhances CPS-MAC performance and is evaluated against traditional WSN protocols. Chapter 5 discusses packet error prediction using preamble sampling and its potential benefits for cooperation. We discuss our simulation framework based on OMNet ++ in Chapter 6. Chapter 7 summarizes the findings of the thesis and presents the conclusions.

Chapter 2

Cooperative MAC Protocols in Wireless LANs and Wireless Sensor Networks

Cooperative communication in WLAN technology has received the bulk of attention from the research community. This is because cooperative communication requires additional energy and WLANs do not suffer from as strict energy and processing constraints as WSNs do. Cooperative MAC protocols for WSNs have also been proposed; however, many of them use the underlying WLAN MAC protocol. This can limit their application in practical WSN deployments.

In this chapter, we present the advances made in developing cooperative MAC protocols for WLANs as well as WSNs [11]. We attempt to categorize these protocols and present an overview of their functionality. We also discuss their results and observed shortcomings.

2.1 Cooperative MAC protocols for WLANs

This section discusses well-known protocols for cooperation in WLANs in detail and presents additional ones in Table 2.2 along with details of features and metrics used for evaluation.

2.1.1 CoopMAC: A Cooperative MAC for Wireless LANs, Liu et al., 2005

CoopMAC illustrates how the legacy IEEE 802.11 distributed coordination function (DCF) [20] can be modified to use cooperative communication, thus achieving both higher throughput and lower interference [38].

In CoopMAC, nodes have the option of switching between direct and cooperative transmission. When using cooperative transmission, a sender communicating with a receiver at a low data rate can ask a neighboring helper, with a higher data rate with both itself and the destination, for cooperation by forwarding its packets. To select this helper, each node maintains a list of potential helper nodes in a CoopTable, as shown in Table 2.1. Alternatively, when using the infrastructure mode, the AP can also maintain such a CoopTable for each node while individual nodes only need to keep track of the AP.

Table 2.1: CoopTable format

ID (28 bits)	**Time (8 bits)**	R_{hd} **(8bits)**	R_{sd} **(8bits)**	**Number of Failures**
MAC address of helper 1	Time the last packet received from helper 1	Transmission rate between helper 1 and destination	Transmission rate between source and helper 1	Number of sequential transmission failures when using this node as helper
....	....	....	....	....
....	....	....	....	....
MAC address of helper N	Time the last packet received from helper N	Transmission rate between helper N and destination	Transmission rate between source and helper N	Number of sequential transmission failures when using this node as helper

To fill this CoopTable with appropriate data, a node passively overhears all ongoing transmissions. To understand this, consider a network with a source S, helper H, and destination D. Assume that S already knows R_{sd}, the data rate supported between itself and D, from the preceding transmissions. To determine if a neighboring node H can cooperate with S by forwarding data to D, it overhears and analyzes transmissions sent from H to D, including both the RTS/CTS packets and the data packets. The date rate being used between H and D, R_{hd}, can be retrieved from the Physical Layer Convergence Procedure (PLCP) header, which is prepended to every frame. Finally, S makes an estimate of the rate between itself and H, R_{sh}, using the received signal power and assuming symmetric channels. All this information is stored in the CoopTable, along with timestamps and any consecutive failed cooperation attempt by H.

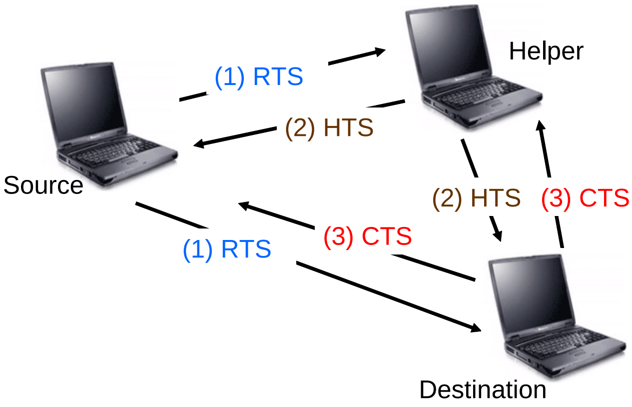


FIGURE 2.1: CoopMAC handshake

When S wants to send data to D, it calculates the amount of time required to send the data using both the direct link S → D and using the helper node S→ H → D. This simply involves adding up the payload size, header size, and control packet size and dividing it up by the corresponding transmission rate, which is stored in the CoopTable. If the S→ H → D is more time-efficient than the direct link S → D, CoopMAC uses cooperation. For cooperative handshaking, an additional frame HTS (Helper ready To Send) is introduced, as show in Figure 2.1. The source puts the address of both the helper and the destination in the RTS frame along with the request to cooperate. The helper, if available, acknowledges this with an HTS. Finally, the destination replies with a CTS followed by the data transfer.

A feature of CoopMAC is that it can use the existing frame fields for addressing and does not require new addressing fields in headers. This allows it to be backwards-compatible with the IEEE 802.11 protocol and nodes can switch between cooperative and non-cooperative transmission. Frame formatting and addressing details can be found in reference [38]. Results show that CoopMAC can achieve substantial throughput and delay improvements, without incurring significant complexity in system design. A related work [43] shows that such a cooperative scheme can also lead to energy savings for the helper nodes. This is because by forwarding data for low data rate stations, a helper node can save time, which translates into energy savings. However, such savings at node level might not translate to energy savings for the entire network.

A drawback of CoopMAC is that it either uses the direct source-destination channel or the source-relay-destination channel. As only one packet is delivered to the destination, the destination cannot use a packed combining scheme and take advantage of redundancy in the form of a repeated packet. Therefore, CoopMAC, in a strict sense, is not a cooperative protocol as its diversity degree is only one.

2.1.2 Mobile Cooperative WLAN. MAC and Transceiver Design, Prototyping, and Field Measurements, Valentin et al., 2008

The work of Valentin et al. focuses on the practical implementation aspects of cooperative diversity protocols [44]. They have extended the IEEE 802.11 protocol by introducing a new signaling packet, namely cooperative RTS (cRTS), shown in Figure 2.2.

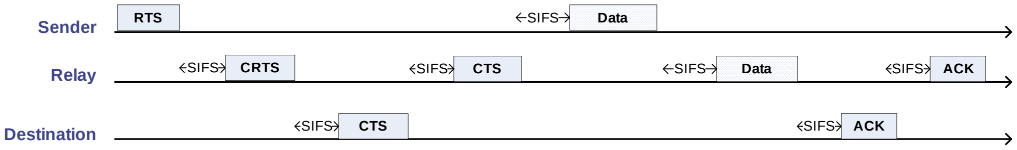


FIGURE 2.2: 802.11 with cooperative signaling, cRTS, Valentin et al.

A source sends out an RTS packet which, in addition to the source and the destination address, also includes a relay address. When the relay node receives this RTS, it sends out a cRTS to indicate its presence and willingness to cooperate. The destination replies with a CTS frame, which is repeated by the relay to complete the handshaking procedure. Then, the source transmits the data, followed by a retransmission from the relay which uses the decode-and-forward strategy to make retransmission decisions. Finally, the destination acknowledges the successful reception by using an ACK, which is also repeated by the relay. This scheme provides diversity for both the data packets and the control packets.

The performance of the protocol was evaluated in a real-world scenario where software-defined radios (called SORBAS) were used for implementation. SORBAS runs a fully programmable IEEE 802.11g stack, which was updated to include cooperative signaling. Results show that the cooperative protocol can significantly improve the packet error rate compared to direct transmission in both an indoor scenario without mobility and an outdoor scenario with mobility. Due to the extra signaling and communication overhead, direct transmission outperforms cooperative transmission at high transmission powers, but at low transmission power, where direct communication becomes impossible, cooperative communication still allows nodes to communicate. This protocol achieves a diversity degree of two.

We observe that for this scheme to work, changes have to be made to IEEE 802.11 frames which renders them incompatible with existing implementations. To ensure backward compatibility, a mechanism for interoperability with legacy devices would be needed. This work also does not evaluate effects on energy consumption.

2.1.3 PRCSMA: Persistent Relay Carrier Sensing Multiple Access, Alonso-Zarate et al., 2008

The work by Alonso-Zerate et al. proposes PRCSMA, a distributed cooperative ARQ scheme, to enhance the performance and coverage of the IEEE 802.11 DCF mode [45, 46]. In PRCSMA, a transmission between a source and destination is overheard by all neighboring nodes in promiscuous mode and buffered. Cooperation is initiated on demand by the destination when it fails to decode a non-cooperative transmission from the source. The destination broadcasts a claim-for-cooperation (CFC) packet to the neighboring nodes to request retransmission, as shown in Figure 2.3. After receiving the CFC, neighboring nodes that have overheard the original transmission act as relays and enter a contention phase by setting up their respective random backoff timers. The relay node whose backoff timer expires first retransmits the packet while other node(s) pause their timers and wait for the medium to become free. At the end of the retransmission, all relay nodes enter the contention phase again by resuming or resetting their backoff timers. This retransmit cycle continues until the destination acknowledges successful reception of the packet or notifies that the maximum retry limit has been reached by using a Negative Acknowledgment (NACK). At this point, the cooperation phase ends and relay nodes delete the buffered packet. Priority to control packets and data packets is assigned using interframe spacing, as show in Figure 2.3, with SIFS being shorter than DIFS and thus providing higher priority for transmission. While most of the other cooperative protocols usually attempt to select one or more relays prior to initiating cooperation for optimized handshaking, an interesting feature of PRCSMA is its ability to use a varying number of relays sequentially for ARQ.

The performance of this distributed cooperative ARQ protocol has been evaluated in terms of the average packet transmission delay, defined as the average duration of the first failed transmission plus the average time required to complete a successful cooperation phase for a given number of retransmissions. The performance is compared with the traditional ARQ scheme for a varying number of average retransmissions required,

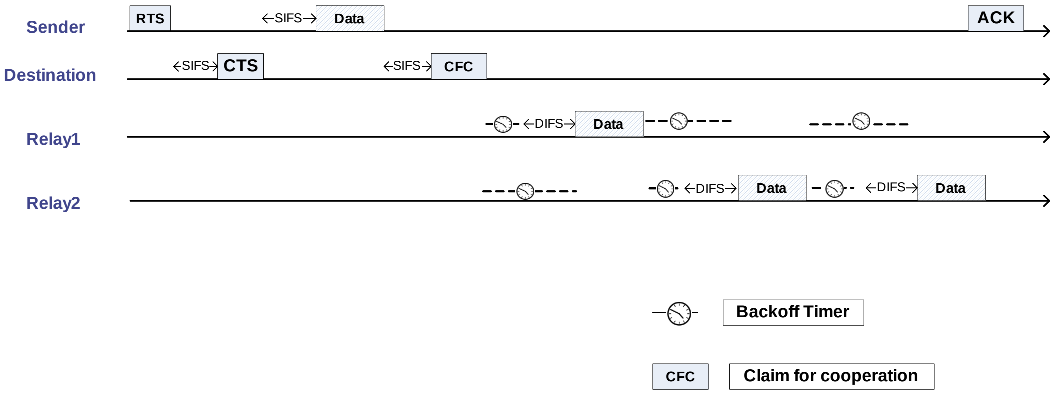


Figure 2.3: PRCSMA, Alonso-Zerate et al.

active relays, and different contention window (CW) sizes. Analytical and simulation results show that the ratio of data rates between source-destination and relay-destination determines the efficiency of the scheme. A retransmission from a relay with a higher data rate can reduce the retransmission delay compared to retransmission from a source node with a lower data rate. The presence of a large number of nodes in the neighborhood can lead to collisions and careful selection of CW size is suggested. Also, different strategies for selecting the appropriate relays for such a cooperative ARQ scheme have been discussed in related work by the same authors in reference [47]. Application of PRCSMA in multi-radio cellular networks was discussed in reference [46].

Energy consumption has not been discussed in this work. However, as the nodes listen to all ongoing transmissions using the promiscuous mode, this active listening could possibly result in a higher overall network energy consumption as compared to legacy IEEE 802.11. Analyzing the tradeoff between a reduced delay and the corresponding price paid in energy consumption could be interesting.

A related work by the same authors looks at the energy consumption of a simpler cooperative ARQ scheme in low-power networks such as IEEE 802.15.4 networks [48, 49]. The scheme uses a coordinator to manage cooperation and relay nodes. It concludes that in cooperation, additional energy usage by relays can be justified by the corresponding improvement in outage probability. However, cooperation should only be used when needed, i.e., when the channel conditions between the source and destination are unreliable.

A slightly modified version of this protocol that uses network coding instead of simple retransmission is presented in reference [50].

2.1.4 C-MAC, Aytac Azgin et al., 2005

Aytac Azgin et al. proposed C-MAC in 2005 [51]. C-MAC uses RTS/CTS for handshaking and includes a method for relay selection. This protocol assumes that a source already knows potential relays, network connectivity, and other neighborhood information, found by using *hello* packets. Cooperating nodes transmit simultaneously by using CDMA, where transmissions are assumed to be completely synchronized so that the signal containing the same data arrives at the receiver coherently and can benefit from constructive interference. This assumption, in practice, might not be practical because CDMA transmissions, by design, do not need to be precisely synchronized and would not constructively interfere.

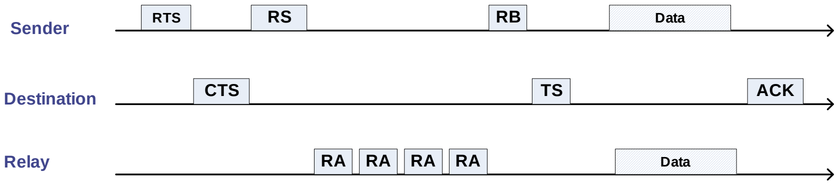


Figure 2.4: C-MAC, Azgin et al.

In C-MAC, a relay and source node use orthogonal chip sequences. The source node uses a predetermined chip sequence. Lest two relays use the same chip sequence, relay nodes negotiate chip sequences by exchanging control packets with the source and other potential relays during the handshaking phase. C-MAC functioning is shown in Figure 2.4. The source starts by sending an RTS packet. The destination replies with a CTS packet, which also includes a list of unavailable chip sequences for relay nodes. The source node then begins the relay selection phase by sending a Relay-Start (RS) packet which includes a list of potential relays as well as the order in which they should reply to the RS packet. After receiving the RS packet, each relay node transmits a Relay-Acknowledgment (RA) packet in the order indicated by the source node. RA packets carry information on potential chip sequences which can be assigned to the node by the source. After receiving the RA packet, the source selects relay nodes, assigns them a transmit power level, and sends this information in a Relay-Broadcasting (RB) packet. Here it is assumed that nodes know and exchange with each other the relative location that can be used to determine optimum transmit power levels. Details on determining the power levels can be found in reference [51]. Then the destination broadcasts the Transmission-Start (TS) packet which indicates the chip sequences to be used during the data transmission phase so it can be marked unavailable by neighboring nodes not participating in the current cooperation phase. Finally, the data transmission commences where both the source and the relay node simultaneously transmit data to the destination, which acknowledges the successful reception.

It is important to mention here that in order for source and relays to simultaneously transmit data, relays must have already received a copy of the packet before cooperative transmission initiates. How this would be accomplished in C-MAC is not discussed. If such an exchange between the source and relay requires a separate handshaking phase, it could lead to significant overhead. This can be avoided by simply introducing this source-relay packet exchange between the relay selection and the data transmission phase in Figure 2.4.

A scheme for finding a cooperative end-to-end routing path is also proposed, which requires that the sender node be able to determine the angle of arrival for the signals transmitted by the relay nodes. Determining this angle of arrival is known from sector antennas used in systems such as GSM. However, IEEE 802.11 transceivers are usually equipped with single omni-directional antenna, which means that the angle of arrival assumption constrains the feasibility of such a routing scheme.

Another weakness of this scheme appears to be the strict need for time synchronization. As mentioned previously, CDMA transmissions, by design, do not need to be precisely synchronized and would not constructively interfere. The protocol also incorporates a considerable handshaking overhead. Furthermore, C-MAC exploits only cooperative diversity for the data packets. Unreliable delivery of the control packets can limit the applicability of a cooperative protocol. The effect of lost control packets and according recovery mechanism is also not discussed. The results do not address latency or throughput performance.

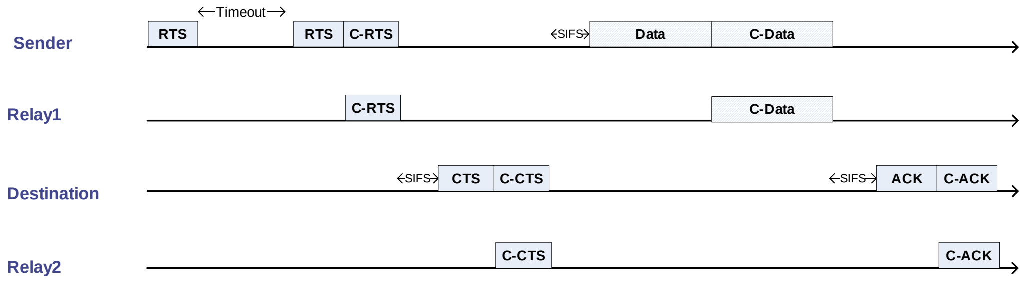


Figure 2.5: CD-MAC handshake, Moh et al.

2.1.5 CD-MAC, Moh et al., 2007

Cooperative Diversity MAC (CD-MAC), proposed in 2007, is based on the DCF mode of the IEEE 802.11 standard [52]. In CD-MAC, nodes use Distributed Space-Time Coding (DSTC), which is a distributed multi-user version of Space-Time Block Coding (STBC) [53].

In STBC, the sender encodes and modulates the information bits to be conveyed to the receiver and maps the source signal to multiple transmit antennae (space diversity), which simultaneously transmit the signal. The receiver demodulates and decodes the signal received on each of the receive antennas. While it is necessary to have multiple transmit antennas, it is not necessary to have multiple receive antennas. This, however, limits the advantages. For situations where nodes have only a single antenna for transmission and reception, DSTC can still be used. Here, transmission of multiple copies of a data stream is distributed among the cooperating nodes, which act as a virtual antenna array. The nodes encode the data by using orthogonal codes and simultaneously transmit it to the destination, thus forming a virtual multiple-input-multiple-output (MIMO) system. However, issues such as distribution of data, coordination among nodes, and synchronization should be addressed. Readers interested in details of DSTC are referred to references [52, 54].

Packet scheduling in CD-MAC resembles an ARQ scheme where cooperation is activated when a direct transmission of a control packet fails. As shown in Figure 2.5, a source node sends an RTS to the destination. If the destination replies with a CTS, then the succeeding data transfer is done without cooperation.

However, as shown in Figure 2.5, if the source fails to receive a CTS from the destination node and the timeout period expires, it activates cooperation in the next phase. The source signals this to the receiving nodes by using a relay address in the repeated RTS packet. During cooperation, the source and relay both use DSTC, where the source first sends a packet to the relay in the first phase and then both the source and relay simultaneously transmit coded copies of the same packet to the destination. In Figure 2.5, C-RTS represents coded RTS, which means DSTC is also utilized for control packets. When the destination wants to reply to a C-RTS, it also selects a relay and sends a C-CTS simultaneously with the relay. Following this, data transmission and ACK packets are transmitted.

For relay selection, nodes keep an estimate of the link quality with neighboring nodes by monitoring or overhearing transmissions. This can be done by using broadcast *hello* packets. An implicit assumption made here is that the channels are symmetric, which might not be the case in a real-world scenario. CD-MAC has been simulated in NS2 and its performance compared with the DCF mode of the IEEE 802.11 standard. Results show that CD-MAC can achieve a better packet delivery ratio for varying levels of noise and movement speed. However, the nodes have to pay the price in terms of end-to-end latency.

We observe that CD-MAC does not address synchronization which is needed for DSTC. Also, CD-MAC does not address the case when a selected relay goes offline or is unavailable. Although energy consumption is not discussed, intuitively it appears that CD-MAC would have a higher latency because each transmission in repeated twice, regardless of whether the original uncoded transmission was successful or not.

2.1.6 Cooperative MAC Protocol with Automatic Relay Selection in Distributed Wireless Networks, Chou et al., 2007

Chou et al. proposed this protocol in 2007 with focus on the relay selection problem [40]. The two main points addressed are when to cooperate and with whom to cooperate. The protocol allows a relay node to cooperate only when needed. The decision to cooperate is done during handshaking. Furthermore, if the nodes decide to use cooperation, only one relay is selected to participate.

This work is also based on the DCF mode of the IEEE 802.11 protocol. As shown in Figure 2.6, the source starts by sending an RTS packet, which includes the intended data rate $\mathrm{R_d}$ for data transmission. Then, the destination replies with a CTS packet and piggybacks the source-destination channel quality estimated by the signal-to-noise ratio ($\mathrm{SNR_{sd}}$). Any node which receives only the RTS or the CTS is not considered a potential relay since it is outside the transmission range of either the source or the destination. Nodes which have received both the RTS and CTS packet are potential relays. The RTS and CTS packets are used by each potential relay to determine $\mathrm{SNR_{rs}}$ and $\mathrm{SNR_{rd}}$, respectively. The relay can additionally retrieve $\mathrm{SNR_{sd}}$ from the CTS packet. Substituting these SNR values in the Shannon-Hartley theorem and comparing the result with $\mathrm{R_d}$, the relay can determine if it is possible to achieve the desired rate by using direct transmission or cooperative transmission. If cooperation is desirable, a relay node would send a busy tone in the slot succeeding the CTS. This busy tone is meant to indicate to the source the relay's willingness to cooperate and to other potential relays the fact that a relay has already been selected so they can stop contending. Then, the relay sends a Relay-Ready-to-Send (RRTS) packet with a NAV updated to include additional time needed for cooperation. Following this, first the source transmits the data which is retransmitted by the relay. Finally, the destination acknowledges the packet. Details can be found in reference [40].

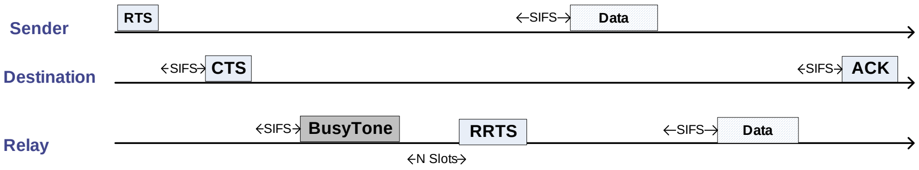


FIGURE 2.6: Cooperative MAC protocol with automatic relay selection, Chou et al.

An interesting point is the use of the Shannon-Hartley theorem to determine if a desired rate can be achieved by a node. While Shannon-Hartley provides a theoretical maximum limit, a more practical alternative could be to look at the possible modulation techniques provided by the hardware and the corresponding maximum data rates possible.
The authors have further presented an outage analysis. Performance evaluation of the MAC protocol as well as energy-efficiency considerations were left for future studies.

2.1.7 Other Cooperative MAC protocols for WLAN

For readers interested in a more comprehensive overview, Table 2.2 lists more cooperative MAC protocols for WLAN along with features and performance metrics.

2.2 Cooperative Medium Access Control Protocols in WSNs

2.2.1 Cooperative Communication for Wireless Sensors Network: A Mac Protocol solution, Mainaud et al., 2008

Mainaud et al. proposed WSC-MAC, which focuses on selecting a relay among the neighboring nodes [25]. The idea is to introduce a Group Identifier ID (GID) for relay selection, which is auto-configured during the initialization phase. This GID would be used later to limit the number of relays to one. This is done by preventing the neighboring nodes from selecting the same GID. When a node wants to send a packet, it would randomly select a GID from a list of possible GIDs. The selected GID is put inside a packet header and sent to the neighboring nodes. Nodes that receive the

Table 2.2: Other cooperative MAC protocols for WLAN

Name and Year	**MAC Scheme**	**Partner Lookup Scheme**	**Num of Relays**	**Cooperation Initiation**	**Performance Metric(s)**	**Additional Comments**
rDCF, 2006, Zhu et al., [55]	IEEE 802.11 DCF	Yes, uses channel state information (CSI)	1	Sender-initiated	Throughput, delay	CSI gathering via passive overhearing, periodic data exchange
CODE, 2007, Tan et al., [56]	IEEE 802.11 DCF	Yes, similar to rDCF	1 or 2	Sender-initiated	Throughput, delay	Uses network coding
C-MAC, 2009, Jin et al., [39]	IEEE 802.11 DCF	No	1	Sender-initiated and negotiated during handshake	Throughput	Simulation results only
Cross-layer MAC, 2009, Shan et al., [57]	IEEE 802.11 DCF and Busy Tones	Uses distributed scheme proposed in [58]	1	Helper / Relay-initiated	Throughput	Requires multiple channels for busy tones
2rcMAC, 2011, Khalid et al., [59]	IEEE 802.11 DCF	Yes, CSI gathering via passive overhearing	2	Relay-initiated with conflict resolution using special relay response (RR) frame	Throughput and delay comparison with CoopMAC [38] and utdMAC [60]	Uses two relays to provide higher throughput and higher probability of success
Cross-Layer MAC, 2011, Shan et al., [61]	IEEE 802.11 DCF	Distributed scheme, CSI gathering using RTS/CTS	1	Relay-initiated	Throughput / Delay plotted against network radius	Identifies when cooperation helps, No energy discussion
utdMAC, 2007, Agarwal et al., [60]	IEEE 802.11b DCF	Assumes relay is preselected	1	Relay-initiated	Throughput and delay	Compared to IEEE 802.11 for different bit rates
Coop MAC, 2009, Lu et al., [62]	IEEE 802.11 DCF	-	1 or more	Source-initiated	Throughput	Relay node uses decode and forward
COMAC, 2008, Gokturk et al., [63]	IEEE 802.11g	-	1 or more	Source-initiated	Throughput and energy	-

packet retrieve the GID and compare it with their own GID. If the GID from the source node matches their own predetermined GID, they could become a relay for this communication. Otherwise, the packet is dropped. It is important to mention here that this scheme is opportunistic and does not provide a guarantee that at least one relay will always be selected.

In order to set up a GID, each node selects a random number uniformly distributed between 0 and A, the average number of neighbors in the network, calculated as a function of the network size R and the number of nodes present in the network. The difference between network size R and number of nodes has not been clarified. As soon as a node selects a GID, it sends a broadcast packet containing this GID. A neighboring node which has not yet selected a GID would retrieve the GID from the broadcast packet and remove it from its list of potential GIDs. A node would keep on updating its list as long as it keeps on receiving broadcast packets. After a wait timeout, the node would select a random GID from the update list and broadcast its own GID value.

WSC-MAC also includes a link-state evaluation algorithm. Each node maintains a link-state table that stores the link quality between neighboring nodes. A relay R, selected using the protocol above, would only cooperate if the link quality between itself and the destination is better than the direct source-destination link.

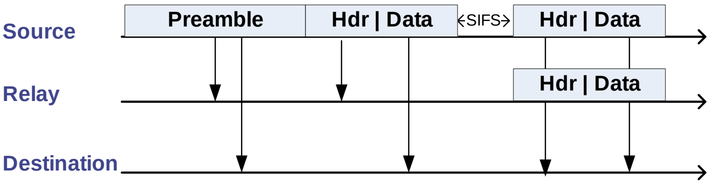


Figure 2.7: WSC-MAC Frame exchange sequence

Figure 2.7 shows the frame exchange sequence of WSC-MAC. A source first sends out a preamble packet to its neighboring nodes. This preamble packet is meant to wake up and synchronize the neighboring nodes. Then, the source transmits a packet containing a header (hdr) and data to the relay and destination. Following this, both the source and relay retransmit the packet simultaneously, using space-time coding, to the destination. The performance of WSC-MAC was studied by using MATLAB simulations. Factors such as the packet delivery ratio (PDR) and network capacity have been evaluated as a function of network density. Results show that cooperative communication can outperform direct transmission in terms of the packet delivery rate (PDR) and network capacity.

We observe that these gains are limited for cases where network density is low. For higher network density, the performance of cooperative and direct transmission becomes the same. The scheme also does not provide a solution for the case in which no relay or more than one relay is selected for cooperation. Also, the relay selection procedure can limit the application of WSC-MAC to fixed or stationary networks because the GID is configured during an initialization phase at startup and, for mobile WSN, it would need to be reconfigured every time there is a significant change in network topology. The effects of WSC-MAC on energy efficiency are not discussed.

2.2.2 Enabling cooperative communication and diversity combination in IEEE 802.15.4 wireless networks using off-the-shelf sensor motes, Ilyas et al., 2011

Ilyas et al. proposed *Generalized Poor Man's SIMO System* (gPMSS) which implements cooperative communication for sensor hardware based on the IEEE 802.15.4 standard [26, 48]. gPMSS uses cooperation for transmitting additional copies of data to the destination. At the destination, diversity combining techniques including selection combining, maximal ratio combining (MRC), and equal gain combining are used.

gPMSS introduces a bit error rate (BER) estimation model which is used by receivers to estimate the number of errors in an erroneously received packet. It is important to mention here that BER is not directly observable because error checking methods such as the cyclic redundancy check (CRC) identify the presence of bit error(s) but not the number of errors present. This scheme can also be used in conjunction with error correction codes, currently available in the IEEE 802.15.4 chip sets, which can reduce the number of erroneous bit errors. To estimate the BER, gPMSS uses both the Link Quality Indicator (LQI) and the Received Signal Strength Indicator (RSSI) measurement which is mandated by the IEEE 802.15.4 standard [64]. The benefit of the BER estimate is that erroneous packets can be categorized based on the number of bit errors in them. This allows packets with a lower BER estimate to be assigned a higher priority during diversity combining. Accordingly, gPMSS integrates this BER estimation with selection combining and maximum ratio combining.

gPMSS does not introduce/require changes to the frame format of IEEE 802.15.4. It simply uses the payload section to integrate its own frame inside the existing frame. The frame includes cooperation information such as addresses, sequence numbers, etc.

The operation of the gPMSS protocol is as follows. The source transmits to the destination and relays. If the transmission is successful, the destination sends an ACK and no retransmission is needed. However, if the original transmission fails, the packet is retransmitted by either one relay that correctly received the packet, or if none of them correctly receives the packet, then all the relays retransmit the erroneous packet that they received. Nodes infer this coordination by using timeouts, receiving acknowledgments, and observing retransmissions from neighboring nodes. Accordingly, the destination performs diversity combining and sends acknowledgment. If the destination is unable to decode the packet after all the retransmissions and does not transmit an ACK, the source itself retransmits, initiating a similar cycle again.

The protocol has been experimentally evaluated with the network consisting of one source, one destination, and two relays. Results show that gPMSS is able to increase the performance by 150% to 245%, in terms of the packet reception rate (PRR), which is a very significant increase. As gPMSS shifts the responsibility of retransmissions to relays, the energy consumption shifts accordingly. While gPMSS is able to save energy at the sender side, additional energy has to be consumed at the receivers for retransmission. This offsets the energy benefits gained at the sender side. However, the increase in PRR means that the energy spent per correctly received packet can be reduced.

It is important to note that in the above mentioned network configuration with a single source, wireless channel effects such as channel contention and collision among different senders are not present. In real-world systems, these factors significantly affect the performance of a protocol. Accordingly, the performance of gPMSS might change when evaluated in a scenario with multiple sources intending to transmit simultaneously to a single or multiple destinations.

2.2.3 Novel Cooperative MAC Protocol for WSN Based on NDMA, Ji et al., 2006

This MAC protocol is based on Network-assisted Diversity Multiple Access (NDMA) [65]. In NDMA, any packet that is involved in a collision is stored in memory and later used for combining with retransmissions. The retransmissions are initiated in the slots following the collision. This scheme attempts to avoid the throughput penalty induced by collision. Details on NDMA can be found in reference [66].

The idea in this protocol is that nodes should cooperate when a direct transmission results in a collision. As detecting collisions in a wireless environment is non-trivial, the question is how this protocol detects collisions and distinguishes them from other factors such as interference due to multi-path propagation or fast fading.

In this protocol, idle nodes continuously overhear the medium to detect potential transmissions between other nodes. Here, it is assumed that when an idle node overhears a transmission, it records the identifier (ID) of the source node. Even when a collision is detected, the idle node can retrieve the IDs of nodes whose transmissions were involved in the collision and store them in a list called a collision list (CL). The assumption that the header of a packet will stay intact in the case of a packet collision is counter-intuitive. Once a collision is detected, all nodes which have overheard the packet enter a Cooperative Transmission Epoch (CTE). The start of a CTE is indicated by the destination node sending a control bit. Idle nodes which have overheard the collided transmission previously transmit their CL to the destination through a control channel. Then the destination allocates slots to these nodes during which they retransmit the packet overheard in the previous phase. Finally, when the collided packets have been recovered by the destination, it sends feedback on the control channel. This acts as an acknowledgment for the source node and as an end of CTE for other nodes.

For evaluation, throughput of this protocol, measured against varying traffic load, has been compared to NDMA. The new protocol outperforms NDMA at high traffic loads. We observe that the energy consumption of this protocol has not been discussed. Such an analysis can elaborate the cost, in terms of energy consumption, of integrating cooperation into NDMA. Also, analyzing the behavior of this protocol in a densely deployed network, where collisions are significant, can also be interesting.

2.2.4 Two-Transmitter Two-Receiver Cooperative MAC Protocol: Cross-Layer Design and Performance Analysis, Zhou et al., 2010

Zhou et al. proposed the cross-layer MAC (CC-MAC) which combines space-time coding and adaptive modulation at the physical layer and uses ARQ at the data link layer [67]. In conventional communication, when a source S wants to communicate with destination D, a conventional routing protocol can be used to determine the non-cooperative path $S \to A \to B \to C \to D$, shown in Figure 2.8 by solid lines.

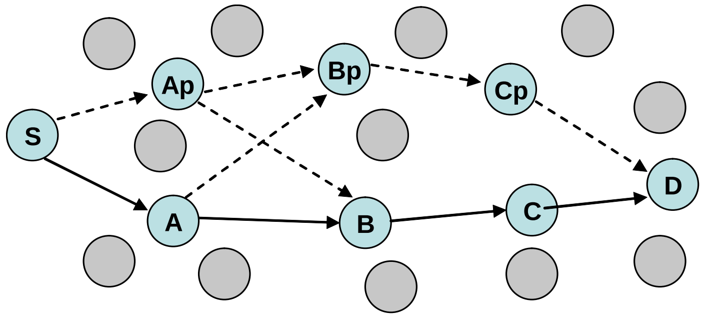


FIGURE 2.8: CC-MAC route establishment and MIMO, Zhou et al.

In CC-MAC, nodes use the same conventional routing path, shown by a dotted line in Figure 2.8. In the first phase, S inducts a set of receiving nodes, A and a partner node A_p, denoted by $R_A = \{A, A_p\}$. Following this, nodes in R_A try to receive the data simultaneously from S. Then, both A and A_p become transmitters and induct $R_B = \{B, B_p\}$ as the next hop node for receiving the packet. Nodes in R_A then transmit the data simultaneously to nodes in R_B using space-time coding, acting as a virtual antenna array. After successfully receiving the data packets, the receiving set R_B repeats the process until the packets reach the destination node D. CC-MAC also incorporates an ARQ scheme, retransmitting data based on which node failed to receive the packet. If neither node in the receiver set correctly receives the data, the source node retransmits. However, if one of the two nodes in the receiver set fails to correctly decode the data, the other node retransmits so a complete retransmission cycle from the source can be avoided.

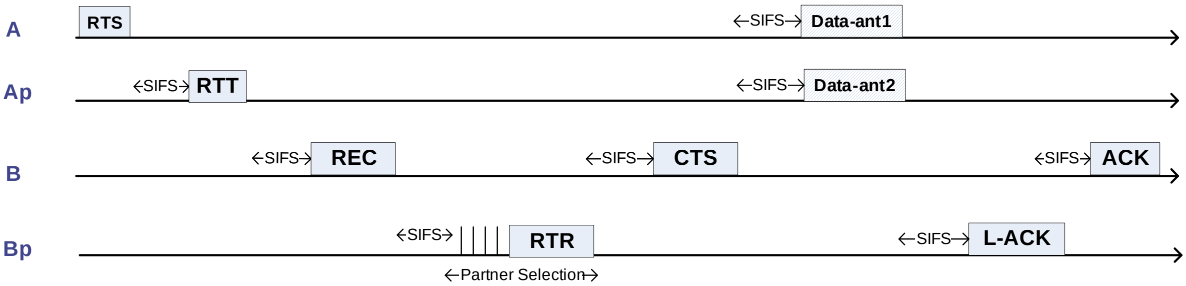


FIGURE 2.9: CC-MAC handshake scheme, Zhou et al.

CC-MAC uses an elaborate handshaking scheme, based on the DCF mode of IEEE 802.11 shown in Figure 2.9. For elaboration, we show a 2x2 communication system where two transmitters $T_A = \{A, A_p\}$ are sending to two receivers $R_B = \{B, B_p\}$. Both nodes in set T_A have already received the packet. To initialize the cooperative transmission, node A sends out an RTS, which is an extension of a regular RTS frame and includes the address of partner A_p. Upon hearing the RTS, if node A_p can cooperate, it replies with a ready-to-transmit (RTT) frame. Node B, after receiving both RTS and RTT, attempts to recruit a partner by sending a recruit (REC) frame. This partner will be a part of the receiving set R_B.

For recruiting a partner, it is assumed that every node, including node B, maintains a distance table which records its one-hop neighbors, discovered by using *hello* packets. Using this distance table, node B selects the nearest K nodes, $B_1, ..., B_k$, and includes all their addresses into the REC frame. The sequence of the addresses in the recruit packet identifies the order in which nodes in $B_{1..k}$ are supposed to acknowledge the REC request. Node B also includes the instantaneous SNR between itself and nodes in set T_A in the REC frame. Potential partners in set $B_{1..k}$, which have received the REC frame and find their address inside, can reply if they satisfy the following two conditions. First, they should have received both the RTS and the RTT. Second, the instantaneous SNR of the potential node with the set T_A should not be smaller than that of the receiver with the set T_A. This requirement ensures that the partner's participation will not lower the instantaneous SNR between the transmitting and receiving sets. The first node from $B_{1..k}$ to reply with a ready-to-receive (RTR) is considered a partner. After that, node B sends a CTS indicating that nodes in receiving set $R_B = \{B, B_P\}$ are ready to receive. Following this, nodes in set T_A transmit simultaneously acting as a virtual MIMO system. After data transmission is complete, node B_P first sends a local-ACK (L-ACK) to B, after which B sends an ACK indicating a successful reception at R_A.

The authors have compared the throughput of CC-MAC with direct transmission by using different modulation techniques. The simulation results show that CC-MAC can achieve better overall throughput compared to direct transmission. The energy efficiency of CC-MAC is also comparable to direct transmission. Throughput of CC-MAC is also compared with the receiver-based auto-rate (RBAR) protocol. CC-MAC for different packet lengths can perform better than RBAR. Also, the size of the network, in number of nodes, does not significantly affect the throughput.

We notice that the last observation is contrary to conventional wisdom and the conclusion presented by Gupta and Kumar in reference [68]. This is because in contention-based protocols, an increase in the number of nodes also increases noise and contention, which directly affects the throughput. Also, this work does not discuss how nodes would be able to achieve synchronization, which is needed for space-time coding.

2.2.5 Cooperative Low Power MAC for WSN, Nacef et al., 2011

Nacef et al. proposed two variants of their Cooperative Low Power MAC (CL-MAC) protocol which differ in relay selection [69]: a reactive CL-MAC(R) which selects a relay after data is transmitted by a source, and a proactive CL-MAC(P) which selects the relay prior to data transmission. Apart from this, both variants are identical and are shown in Figure 2.10.

In CL-MAC, low power listening (LPL) or preamble sampling is used when nodes duty cycle their transceivers. Nodes perform CCA and backoff before transmitting a packet to minimize collisions. When a node has data to send, it sends a sequence of strobed preamble packets to wake up the neighboring nodes. The preamble packet contains rendezvous (RDV) information which indicates the time when handshaking or data transmission will commence. As multiple relay nodes could be awake in the neighborhood, relay selection uses a backoff timer, which is calculated on the basis of the residual energy of the node and channel condition between itself and the destination, based on the last received packet. The relay with the smallest backoff timer transmits first and the rest of the relays backoff and cancel transmission.

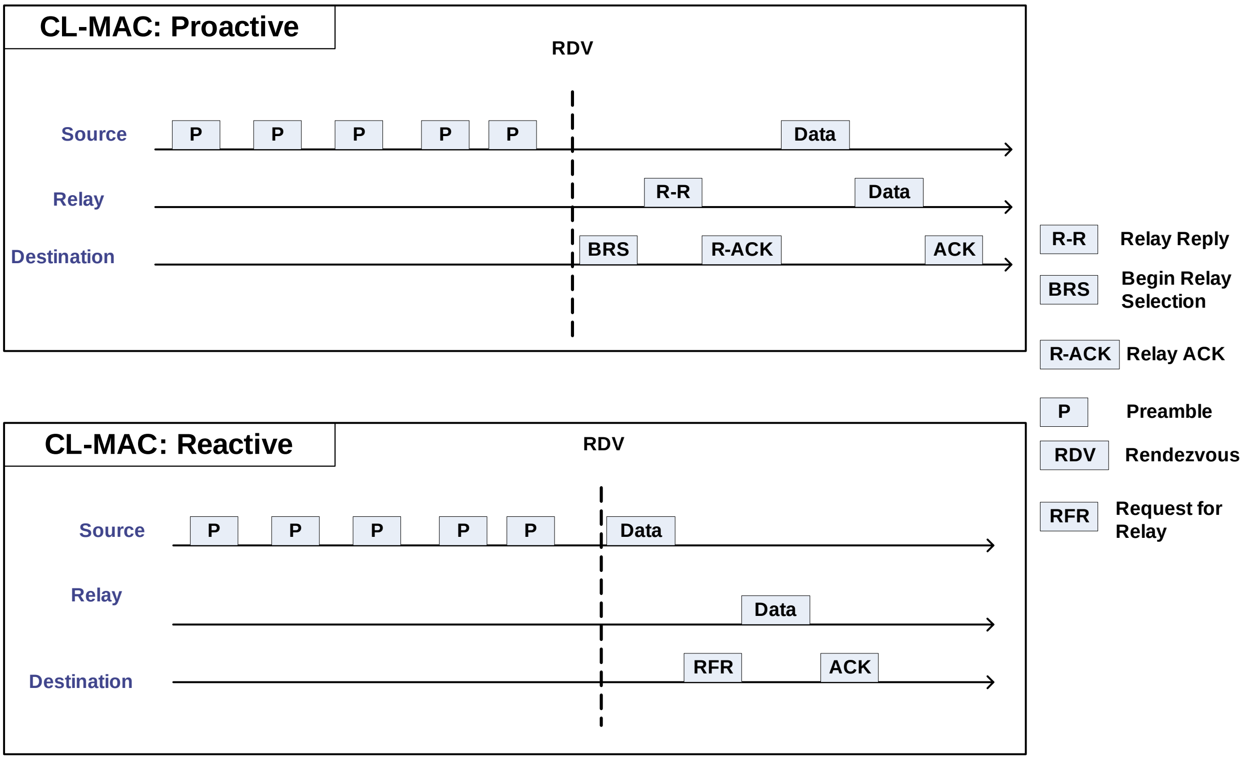


Figure 2.10: CL-MAC, Nacef et al.

In Proactive CL-MAC(P), a relay is always selected but cooperative data transmission is done only when needed. As shown in Figure 2.10, the destination broadcasts a begin relay selection (BRS) packet. Using the relay selection method above, a selected relay sends a relay reply (R-R) message. The destination responds with a relay ACK, after which the source transmits the data. The destination sends an ACK if it receives the packet correctly. The absence of an ACK from the destination results in cooperative transmission from the relay. Finally, the destination acknowledges the cooperative transmission by using an ACK packet.

In reactive CL-MAC(R), relay selection is initiated by the destination when it is unable to decode a direct transmission from the source, as shown in Figure 2.10. To initiate cooperative transmission, the destination sends a request-for-relaying (RFR) packet triggering the relay selection. The only relays participating in relay selection are the ones that have correctly received the packet from the source. The relay with the shortest backoff window retransmits the data which is acknowledged by the destination.

The performance of this protocol has been evaluated by using simulations and is compared to a modified version of X-MAC [33]. The network setup consists of battery-powered source and relay nodes, placed around a sink. The nodes sleep and wake up for 0.09 and 0.01 seconds, respectively. Results show that CL-MAC outperforms X-MAC in terms of outage probability and delivery ratio. For outage probability, as the number of relays are increased, the outage probability decreases for CL-MAC but for X-MAC it does not change as X-MAC does not take advantage of the relay nodes. Also, reactive CL-MAC(R) performs slightly better than proactive CL-MAC(P). Energy consumption results show that while X-MAC uses less energy than CL-MAC when a single relay is available, a large number of relays helps CL-MAC outperform the X-MAC. This is because more relays translates to a better choice of the relay node and therefore fewer retransmissions. The work does not mention how often the source node(s) generate(s) data. This would have been helpful in determining how CL-MAC performs under varying traffic loads and in the presence of contention. Furthermore, it is shown that the performance of both CL-MAC(P) and CL-MAC(R), in terms of outage probability and delivery ratio, does not change when LPL is deactivated. What effect this deactivated LPL version of CL-MAC has on energy consumption is also not discussed.

2.2.6 Other Cooperative MAC Protocols for WSN

Table 2.3 lists more cooperative MAC protocols for WSN along with features and performance metrics.

2.3 Energy Consumption in Cooperative Communication

As cooperative communication involves additional relay nodes and increased coordination and communication among nodes, the cost of this is paid in terms of energy consumption and, possibly, time. In this section, we discuss the energy consumption results of various protocols.

Reference [69] uses the energy-consumed-per-packet metric for measuring energy consumption. In this work, the number of relay nodes is varied and the authors conclude that the number of relays between the source and destination affects the energy consumption. With fewer relays, cooperation is marginally expensive in terms of energy usage, but as the number of relays is increased, there is a slight improvement in energy consumption as there are fewer erroneous retransmissions. However, for almost the same amount of energy as a conventional protocol, their cooperative protocol achieves a significantly higher delivery ratio.

Work by Predojev et al. discusses the energy efficiency of cooperative ARQ protocols in low-power networks [49]. Their simulation setup consists of a convergecast network where nodes are deployed around a coordinator (sink) which is responsible for managing the nodes and cooperative communication among them. The energy efficiency is defined as the energy consumed per successfully transferred bit. Results show that while the energy consumption of such a cooperative scheme is slightly higher than a non-cooperative scheme, it achieves a significant improvement in outage probability. This observation is similar to the work in reference [69], discussed previously.

Zhou et al. [71] propose a cooperative MAC protocol with primary focus on minimizing energy consumption and extending network lifetime. The scheme uses RTS/CTS between source and destination for handshaking, which is also used by nodes to estimate channel conditions for relay selection. As relay nodes are not part of this RTS/CTS message exchange, the protocol assumes symmetric channel conditions. A power control strategy for selecting the best relay and maximizing network lifetime is analytically derived. An interesting feature of the scheme is that a source node can itself retransmit the data if this case minimizes energy consumption. Performance of the proposed protocol

Table 2.3: Other cooperative MAC protocols for WSN

Name and Year	**Medium Access Scheme**	**Partner Lookup Scheme**	**Num of Relays**	**Coop[1] Initiation**	**Performance Metric(s)**	**Additional comments**
LMCRTA, 2012 Zhai et al., [70]	IEEE 802.11 DCF	Yes, based on link cost estimated using residual energy and topology information	1	Destination-initiated	Throughput, network lifetime, residual energy	-
Coop[1] MAC, 2012 Zhou et al., [71]	IEEE 802.11 DCF	Yes, based on channel conditions, estimated using RTS/CTS	1	Source-initiated	Energy per packet, outage probability, throughput, network size, network lifetime	Primary focus on minimizing energy consumption and network lifetime maximization
Cluster based coop mac, Ahmed et al., [72]	Coordinated access ACK but without handshake	Yes, based on RSSI estimate and residual energy	1	-	Energy efficiency, transmission distance, capacity	Primary focus on energy consumption, Results based on simulation in MATALB
Coop[2] MIMO MAC, Yang et al., [73]	Modified version of IEEE 802.11 DCF	Yes, based on BER and energy consumption estimate	Multiple, forming a cluster	Source initiated	Energy consumption, packet delay	Results base on simulation in MATLAB, creates clusters on both the sender and receiver side for relaying, related work in [74]
Coop[3] MIMO MAC, Yang et al., [73]	Modified version of IEEE 802.11 DCF	Yes, based on BER and energy consumption estimate	Multiple, forming a cluster	Source initiated	Energy consumption, packet delay	Results base on simulation in MATLAB, creates clusters on both the sender and receiver side for relaying, related work in [74]
Coop XLM, Gupta et al., [75]	IEEE 802.11 DCF with duty cycling	Yes, based on channel conditions	1 or more	Source initiated	Reliability, energy, latency	Needs location-based information
OCO, Li et al., 2010, [76]	IEEE 802.11 DCF	Yes, based on channel usage information	1	Source initiated	Throughput, reliability, latency, and energy consumption	Related work in [77]. Uses multiple channels. Extensive handshaking scheme to determine available channels and mitigate hidden terminal problem.

is compared with direct transmission by using analytical work and simulations. Results show that for both uniform and non-uniform traffic scenarios, this cooperative scheme provides a better network lifetime and throughput compared to direct transmission for a varying number of data rates and network sizes. The scheme also improves outage probability, which results in energy savings. An interesting observation is that in this scheme, cooperation seems to be beneficial in all cases and does not incur a penalty on energy or throughput. In most of the other schemes there is usually some penalty involved for introducing cooperation. Analyzing and resolving this conflicting behavior between the schemes could be an interesting task. Implementation of this scheme on real sensor nodes and comparison with legacy WSN protocols such as S-MAC, BMAC, and X-MAC could provide more insight into the energy-savings capability of the scheme. Work by Sadek et al. [78] analyzes the cost of using cooperation in terms of energy efficiency. They have focused on optimizing power consumption for varying source-destination separation and for different numbers of relay nodes. They conclude that cooperation is not helpful for smaller distances between the source and destination, but cooperative gains can be achieved for larger distances. This is because overhead in terms of energy consumption of the cooperative transmissions outweighs the benefit for smaller distances, where channel conditions are not bad. A similar attempt at analyzing energy and delay efficiencies for cooperation is done by Wang et al. [79], which concludes that below a certain source-relay distance (80 meters in their particular setup) direct transmission is more energy-efficient. For cases where the source-relay distance is greater than the threshold and cooperative communication is beneficial, the best energy-efficiency gains are achieved when the relay is equidistant from the source and destination.

Similarly, Jayaweera [80] proposed a virtual MIMO scheme based on Alamouti space-time block codes [81] for a data-gathering network. The two primary factors analyzed were the effects of signal attenuation and overhead caused by training sequence bits needed for synchronization. Analytical results for energy efficiency vs. varying transmission distance are presented, which show that even though cooperation incurs additional energy overhead, benefits achieved from cooperation translate to overall energy savings for the network. However, the work suggests careful planning of the system. We can also deduce that parameters which impose significant overhead should be fine-tuned, such as training sequences for synchronization, handshaking between nodes, relay selection, etc.

For readers interested in further information on energy consumption in cooperative systems, we suggest references [70, 72, 82–86].

2.4 Discussion

We have presented a comprehensive literature survey of cooperative MAC protocols for wireless and sensor networks, listed in Table 2.4 along with their performance metrics. We see that protocols for WLAN have reached a certain maturity, owing to significant interest of the research community, and some protocols are quite feasible for deployment on existing hardware, such as CoopMAC. Almost all of the proposed protocols are contention-based and use a modified version of IEEE 802.11 DCF mode for cooperative handshaking.

Table 2.4: Cooperative MAC protocols for WLAN and WSN

Name and Author	**Reliability**	**Energy Efficiency Analysis**	**Throughput**	**Delay**
CoopMAC, Liu et al, [38]	✓	✓	✓	✓
MAC, Valentin et al, [44]	✓		✓	
C-MAC, Aytac Azgin et al, [51]			✓	
CD-MAC, Moh et al, [52]	✓			✓
MAC, Chou et al, [40]	✓		✓	
PRCSMA, Alonso-Zarate et al, [45]	✓	✓		✓
WSC-MAC, Mainaud, [25]	✓		✓	
gPMSS, Ilyas et al, [26]	✓	✓	✓	
MAC, Ji et al, [65]			✓	
CC-MAC, Zhou et al, [67]	✓	✓	✓	
Cl-MAC, Nacef et al, [69]	✓	✓	✓	

Cooperative protocols for WSNs have also received attention in the last few years. However, many protocols do not address the energy consumption effects in such protocols. We reiterate the importance of energy consumption analysis because introducing cooperation can increase energy usage while protocols for WSNs usually strive to conserve energy.

To minimize transmission time, some protocols suggest using space-time coding to simultaneously transmit data by the source and partner, but that is non-trivial to implement in WSN nodes as it requires nodes to stay synchronized and avoid clock drift. Such a synchronization requirement could be expensive in terms of communication overhead and energy consumption for sensor nodes with limited energy and processing power.

We further notice that little effort has been done to compare the performance of cooperative WSN protocols with existing WSN protocols.

From this, the above mentioned limitations in existing protocols are addressed in this thesis with focus on the following design considerations:

- Efficient cooperative handshakes for mitigating hidden and exposed terminal problems
- Energy efficiency-vs.-reliability tradeoff so the cost of using cooperation can be evaluated
- Minimizing cooperative signaling overhead to reduce latency and energy consumption
- Keeping implementation complexity low for WSN protocols
- Comparison with traditional WSN protocols to evaluate the cooperation gains

For readers interested in further information on open issues and challenges on the various layers of OSI model from a cooperative diversity perspective, we suggest reference [87].

Chapter 3

Cooperative Preamble Sampling(CPS) MAC Protocol

In this chapter, we introduce CPS-MAC for improving reliability in WSNs under energy constraints. CPS-MAC was one of the first attempts at exploiting cooperation in a traditional WSN protocol [88]. A multi-hop data gathering network is considered in which sensor nodes are deployed around a sink. Nodes periodically sense data and forward it to next-hop nodes. In such a network, CPS-MAC uses cooperative communication to improve reliability by using overhearing to its advantage. In conventional protocols, overhearing causes nodes to receive packets which are not meant for them. Therefore, these packets are discarded and considered a waste of energy. On the contrary, CPS-MAC intentionally wakes up 1-hop and 2-hop neighbors to improve their chances of overhearing a packet. The overheard packets are buffered and then relayed to the next-hop neighbor, combating channel fading by a cooperative spatial diversity gain. Design challenges such as efficiently waking up neighborhood nodes, minimizing energy overhead, and partner selection are addressed.

3.1 Introduction

We consider an ad hoc multi-hop data gathering network where sensor nodes are deployed around a sink as shown in Figure 3.1. Each node defines its distance from the sink using hop count, which is defined as the minimum number of non-cooperative transmissions required to reach the sink from a given node [89]. The sensor nodes periodically sense the data, wake up the neighboring nodes, and broadcast the data. Neighboring nodes receive the data and the one which is closer to the sink forward it to the next-hop nodes. Data eventually reaches the sink which is responsible for collecting, processing, analyzing, and forwarding the data to a base station.

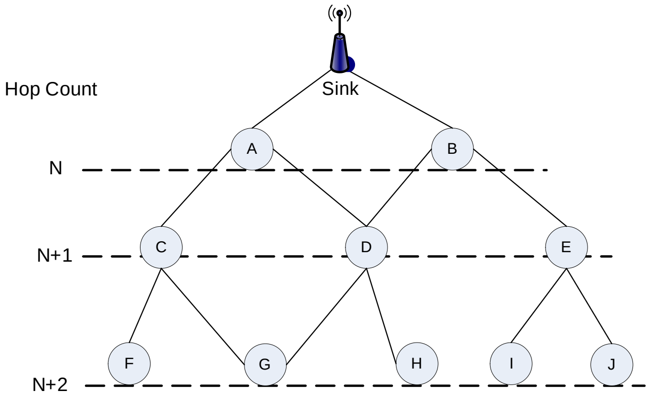


FIGURE 3.1: Data Gathering Network

Before discussing CPS-MAC design, we briefly outline the following challenges faced in developing CC-based MAC protocols for WSNs, along with solutions proposed in CPS-MAC.

1. MAC protocols such as X-MAC try to conserve energy by maximizing the sleep duration of the nodes [33]. CC, on the other hand, increases energy expenditure by requiring nodes to be awake more often. In such a situation, improving reliability and conserving energy may seem counter-intuitive. CPS-MAC compensates for the additional energy expenditure by reducing the time needed to wake up neighboring nodes and by achieving lower packet error rates.

2. Application of CC in densely deployed WSNs can result in multiple nodes overhearing and forwarding a packet and flooding part of the network. In such situations, it could be practical to limit the number of nodes taking part in CC and avoid redundant transmission and energy wastage. To this end, CPS-MAC includes an addressing scheme that attempts to limit one transmission cycle to three nodes and minimizes the number of nodes unnecessarily overhearing the transmission.

3. Under ordinary conditions, data would travel in a hop-by-hop fashion during each transmission. “Hop” refers to a non-cooperative transmission between a single pair of intermediate nodes among the many nodes through which data must pass before reaching destination. CPS-MAC attempts to deliver a packet over two

hops in a single transmission cycle as shown in Figure 3.3. This 2-hop transfer in a single transmission cycle consumes less energy then several single-hop transfers. We explain this 2-hop forwarding in Section 3.1.1. The protocol uses a hop count for this purpose and is explained in Section 3.2 in detail.

3.1.1 Cooperation over multiple hops

In wireless communication, signal propagation ranges can be divided into three categories [90], shown in Figure 3.2.

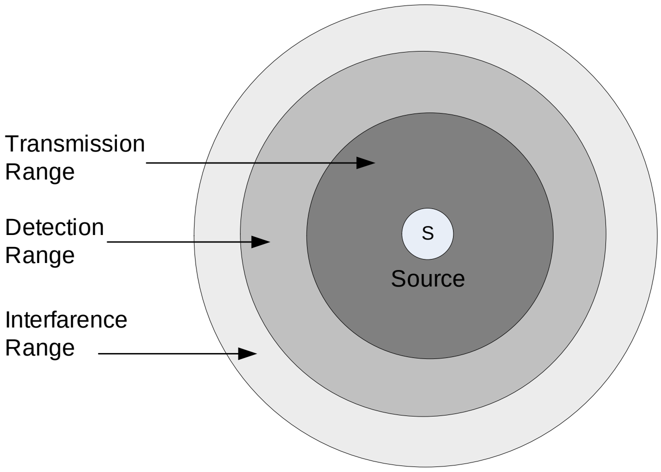


FIGURE 3.2: Signal Propagation Ranges

Within transmission range, communication is possible between source and destination because of the presence of a strong signal. In detection range, the signal can be detected but the error rate is high and little to no communication is possible. In interference range, the destination cannot detect the signal but the signal interferes with communication with other nodes.

While the ranges shown in Figure 3.2 are circular and regular in shape, in practice they would be irregular in shape and time-varying in distance from the source. For CPS-MAC, we are interested in taking advantage of the nodes present in the transmission and detection range. Although these nodes can detect the signal in detection range, albeit erroneously, work by Jekllari et al. shows that the diversity gain achieved by cooperation can provide an extension in the transmission range. This extension in range can increase the broadcast coverage by as much as three times compared to the Single Input Single Ouput (SISO)-based approach [91]. Furthermore, Narayanan et al. [43] and Zhu et al. [55] have shown that 2-hop forwarding leads to higher total network throughput.

This has motivated us to consider 2-hop cooperation for CPS-MAC. 2-hop cooperation means that CPS-MAC will attempt to transmit a packet over two hops, as show in in Figure 3.3. The first hop will be a node which can receive data from the source and hence within its transmission range. This node will act as a partner. The second hop will be a node 2-hops away from the source and 1-hop away from the partner. For densely deployed WSNs, it is likely that there would be nodes in detection range of the source. Using cooperation, CPS-MAC will try to deliver data to these nodes in one cooperative transmission cycle consisting of two phases: a broadcast from source to partner and destination, and followed by broadcast from partner to destination. This means that the redundancy will be propagated over spatially independent channels in the network. This introduces robustness against fading channels. In contrast, a traditional relaying approach would not be able to benefit from this spatial diversity as it would only employ a single source-relay and relay-destination path. Furthermore, if the source to destination transmission fails altogether, the data will still likely be transmitted over one hop to the partner which can later act as a source itself and start another cooperative transmission.

In the next section, we present the protocol design for CPS-MAC.

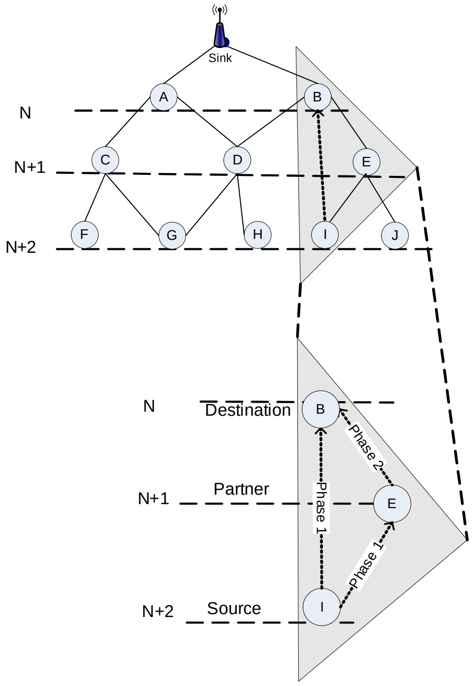


Figure 3.3: Cooperation over multiple hops

3.2 Protocol Design for CPS-MAC

3.2.1 Initialization Phase

In order to make routing decisions and address nodes, CPS-MAC uses hop count values and neighborhood information. To setup this information, we use a flooding algorithm. An example of such an algorithm is the Cost Field Establishment Algorithm (CFEA) [92]. It is executed during the start-up phase of the network. No CC is used during this phase. Consider the hierarchy shown in Figure 3.1. When nodes boot up for the first time, the sink sets its hop count to 0 and nodes set their hop count to ∞. The sink then initiates the algorithm by broadcasting an advertisement (ADV) packet. The content of an ADV packet is shown in Figure 3.4; it contains the node hop count, its own address, and addresses of its 1-hop parent nodes. The addresses of 1-hop parents are needed for addressing and will be explained in the next section.

Figure 3.4: Advertisement (ADV) Packet

The message propagates down from the parent node to its child nodes. We use the term parent and child because nodes in the network are deployed in a hierarchy. Whenever a node receives an ADV message, it determines if it leads to a smaller hop count to the sink. If it does, the node resets its hop count and stores the message's source address as its 1-hop parent and the remaining addresses as 2-hop parent. Then, the node (re-)transmits its own ADV packet.

The 1-hop and 2-hop parent node addresses are stored in a routing table called CoopTable. It additionally stores the addresses of 1-hop child nodes. These addresses are obtained by simply overhearing ADV packets on the media and analyzing the hop count value. This is feasible because nodes do not sleep during the initialization phase and can receive all ADV packets in their reception range. Once a node has calculated its hop count and does not receives a new ADV for the duration of flooding-timeout duration T_f, the initialization phase stops and nodes start their normal operation. At this point, every node will have calculated the optimal hop count to the sink as well as initialized its CoopTable; for example, the node D in the hierarchy above would have a CoopTable as follows:

TABLE 3.1: Node D: CoopTable Parent Nodes

1 hop Parent (Hop Count-1)	2 Hop Parent (Hop Count-2)
A	Sink
B	Sink

TABLE 3.2: Node D: CoopTable Child Nodes

1 Hop Child (Hop Count+1)
G
H

The advantage of using such a scheme is that the source can select a partner and destination prior to transmission, thereby limiting a cooperative transmission to three nodes. This can help in preventing unnecessary flooding of the network. The disadvantage is that, for this scheme to be effective, nodes have to maintain the topology. If the nodes are mobile and the topology changes often, the values in CoopTable would not reflect the actual network configuration. The means that every time a topology change is detected, the *initialization phase* would need to be triggered to update the CoopTables. Depending upon the mobility speed, this operation can prove to be expensive, especially in terms of energy utilization. In the following section, we explain how the CoopTable is used for selecting and addressing nodes for cooperation.

3.2.2 Addressing Scheme

A broadcast transmission from a node to the sink over multiple hops can result in multiple nodes forwarding the same packet along different paths and flooding the network. Though it increases the chances of a packet eventually reaching the sink, nodes have to pay the price of energy expenditure and processing overhead. The problem becomes more complicated when we use cooperative communication because it involves a partner node in addition to the source-destination pair. In order to minimize this overhead and limit the cooperative communication to 3 nodes (source-partner-destination) in each transmission cycle, we use the CoopTable mentioned in Section 3.2.1.

When a node has data to send, it will lookup partner (1-hop parent) and destination (2-hop parent) addresses from the CoopTable. If multiple partner/destination pairs are possible, the source cycles between them to divide the overhead. However, instead of using them as two separate addresses, the node will perform an XOR between them

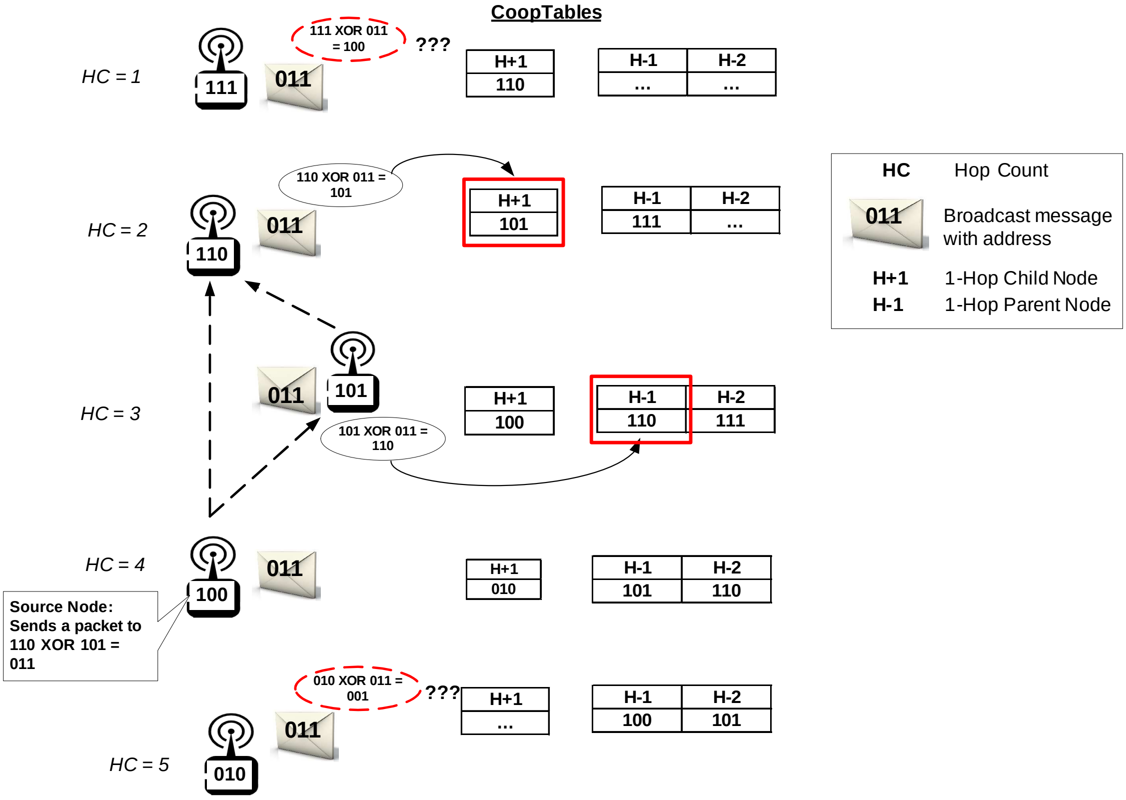


Figure 3.5: Addressing Scheme

and use that value as a single address. Nodes also include their hop count value in the packet.

Once the packet is sent, every node that receives it extracts the address, performs an XOR with its own address, and looks up the result in its CoopTable. Nodes also calculate the hop count difference with the source node and then use the following rules to determine their role (partner/destination) in transmission:

1. If the result matches the address of a parent node and the hop count difference is 1 with the source node, the node acts as partner. In this case, the partner cooperates with the source and retransmits the packet to increase its chances of being received by the destination.

2. If the result matches the address of a child node and the hop count difference with the source node is 2, the node acts as destination.

3. If either the result does not match an entry in the lookup table or if the hop count difference is greater than 2, the node takes no action.

For example, in Figure 3.5, the node with Identifier (ID) 100 sends a packet to node 101 and 110. The XOR of their address is 011, which is included in the data packet. Assuming that all nodes in the neighborhood correctly receive the packet, they decode the address using XOR with their own address. The lookup in the CoopTable for the node 110 and 101 matches the above mentioned rules and they define their roles as destination and partner respectively. The node 111 and 010 are not able to find the resulting address in the CoopTable and therefore do not take part in Cooperation.

In this scheme, there is a probability that the result from the XOR operation might result in collision, i.e., the resulting address can map to a value in the CoopTable even though the node was not addressed, especially when the number of bits used for node identifiers is small. However, the probability significantly reduces when the identifier is large (e.g. 48 bit MAC address).

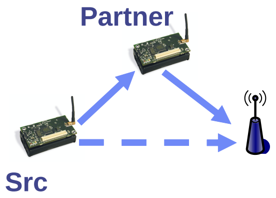


FIGURE 3.6: CPS-MAC

3.2.3 Medium Access Control Layer

We propose a MAC protocol that uses cooperative communication to increase the probability of correct transmission while reducing energy consumption. As discussed in Section 3.1.1, a broadcast transmission can be received by nodes which are multiple hops away from the source but they are discarded as they suffer from bit errors due to fading or attenuation. Our motivation is to utilize even these corrupt packets. The idea is to form cooperative triangles in the network where each triangle consists of source, partner, and destination as shown in Figure 3.3. Nodes cooperate in this triangle to deliver multiple copies of the packet to the destination where packet combining [93] is used to recover the original packet. However, for such a scheme to work, it becomes challenging to wake up nodes which are multiple hops away before initiating a data transmission. To solve this, we propose a wake up scheme which is based on minimum preamble sampling explained in Section 1.2.2.2 [32].

Figure 3.6 elaborates the working of the protocol. When a source node has data to send, it transmits a strobed preamble packet containing synchronization bits and the node's hop count value at the end. The strobed preamble is repeated until the source receives an acknowledgment (ACK) preamble from a neighboring node. When a neighboring node wakes up and receives the preamble, it analyzes the hop count value. If the receiver is not a parent node, it discards the preamble and immediately returns to sleep state to conserve energy. 1-hop parent nodes that receive the preamble contend for the media and the successful node sends an ACK preamble. As no addressing is used in the preamble, any 1-hop parent node can send the ACK preamble. This ACK preamble serves two purposes. First, it will act as wakeup preamble sequence for the next-hop parent. Second, the source will know that some nodes in its 1-hop neighborhood are awake. After receiving the acknowledgment preamble, the source sends the address packet. Nodes analyze the address packet, as explained in Section 3.2.2. If a node cannot define its role, it will return to sleep state to conserve energy. After this, the source broadcasts the data packet. Following this, a partner node acts as follows.

1. If the transmission is not heard by the partner, it will timeout and go to sleep. The source keeps the packet in its queue until the next transmission attempt or until the queue is full.

2. If the transmission is heard by a partner, it uses decode and forward (DAF) [93] to decide if it should again broadcast the packet. In DAF, the partner decodes a received packet to check for bit errors and erroneous packets are discarded. Only if the packet is received correctly, the partner again broadcasts the received packet to the destination.

The destination acts as following.

1. If the transmission is received by destination and decoded correctly, it is sent to the network layer. The network layer tracks and filters redundant packets.

2. If the transmission is erroneously received by the destination, it is buffered for combining later.

3. If the destination receives a retransmitted copy of a previously received erroneous data-packet, it attempts to combine the two copies of the same packet using maximum ratio combining (MRC) [93] to recover the original data. In its simplest

form, MRC is modeled by adding the instantaneous signal-to-noise ratio (SNR) of the two packets received from source and partner. This accumulation of the instantaneous SNR increases the probability at which the destination can reliably decode the packet. If the data is successfully recovered, it is forwarded to the higher layer otherwise the node drop the packets and returns to sleep.

After the transmission, nodes may return to sleep or listen state. The recipient of the data packet will schedule a transmission for further propagation of the data packet towards the sink.

3.3 Performance Evaluation

3.3.1 Simulation Setup

In this section, we present simulation results for CPS-MAC. Simulations are conducted using the Mobility Framework for the OMNeT++ discrete event simulator [94]. Our purpose is to show how the protocol behaves and reacts to typical WSN conditions such as fading channels, extended periods of low data flow, and their effect on power consumption. This gives us a good understanding of how deployment on real sensor nodes would perform.

The performance of CPS-MAC is compared with the minimum preamble sampling (MPS)-based MAC protocol discussed in Section 1.2.2.2. Recall that in such protocols, nodes use MPS for waking up neighboring nodes prior to data transmission. For comparison purpose, we have implemented the following network configuration.

1. Direct-MPS: This scenario consists of two nodes, source and destination as shown in in Figure 3.7. The source transmits directly to the destination and uses MPS to wake up the destination node.

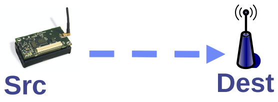


FIGURE 3.7: Direct-MPS

2. Relaying-MPS: In this scenario, an intermediate node is introduced between source and destination as shown in Figure 3.8. The source first wakes up the relay using MPS and transmits the packet; however, no attempt to cooperate with the destination is done. The relay node then wakes up the destination and forwards the

packet, if correctly received from the source. If a node receives correct packets from both the source and relay, it discards the duplicate packet. This is done by keeping a sequence number of correctly received packets.

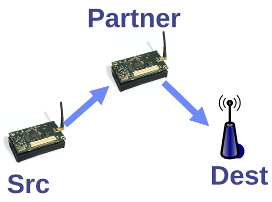


FIGURE 3.8: Relaying-MPS

3. CPS-MAC: This scenario uses our proposed protocol for a 3-node scenario as shown in Figure 3.9. We use cooperation to exploit both the source-destination and source-partner-destination channels prior to data transmission. This is done by the partner repeating the preamble to wake up the destination. The destination can use combining if it receives multiple copies. Additionally, we also show the reliability of CPS-MAC without combining. Here no combining for data packets is performed. This lets us determine whether combining erroneous packets is advantageous.

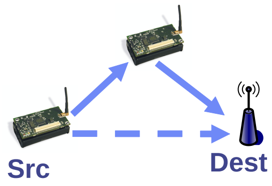


FIGURE 3.9: CPS-MAC

Due to limitations of the *Initialization phase*, discussed in Section 3.2.1, we assume that the environment of the nodes changes, but the network topology remains static. Table 3.3 lists physical and MAC layer parameters used. The physical-layer parameters are based on Chipcon CC1020, a low-power RF transceiver.

3.3.2 Results: 3-Node Network

Our initial performance evaluation focused on a 3-node scenario comprising a single source, partner, and destination node. The nodes were duty cycling to conserve energy; however, the role of each node was predefined to prevent uncertainties introduced by dynamic role selection and to focus on isolated core protocol properties.

TABLE 3.3: List of Parameters

Parameter	**Value**	**Unit**
Bitrate	153.6	Kbps
Packet Length	60	Bytes
Path loss Exponent	3.5	-
Fading Model	Rayleigh Fading	-
Transmit power	-21 to 9	dBm
Current Consumption: Transmit mode	12.3 to 27.1	mA
Current Consumption: Receive mode	19.9	mA
Current Consumption: Power down mode	0.2	μA
Receiver Sensitivity	-104	dBm
Duty Cycling: Sleep Duration	800	ms
Duty Cycling: Listen Duration	200	ms
Simulation Duration	48	hours

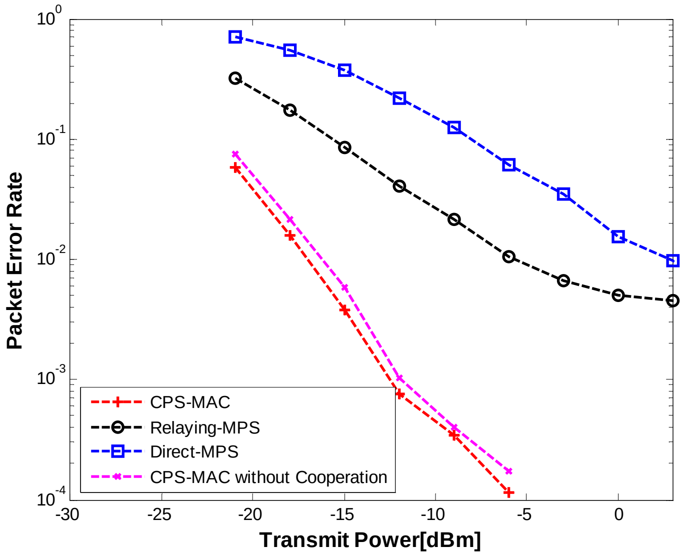


FIGURE 3.10: Packet Error Rate

Figure 3.10 shows the Packet Error Rate (PER) for varying transmission power. As mentioned in Section 3.3.1, we have evaluated CPS-MAC performance both with and without CC. CPS-MAC here achieves a better PER compared to the direct and relaying MPS protocols. This performance improvement over the MPS-based protocol is attributed to the CPS-MAC wake up scheme. This is because repeating the preamble from the partner node increases the chances of the destination node waking up prior to data transmission. This process is similar to CC but here, the preamble packet is repeated at the partner station instead of the data packet. Thus, the destination would receive multiple copies of the preamble packet, increasing its chances of overhearing the preamble.

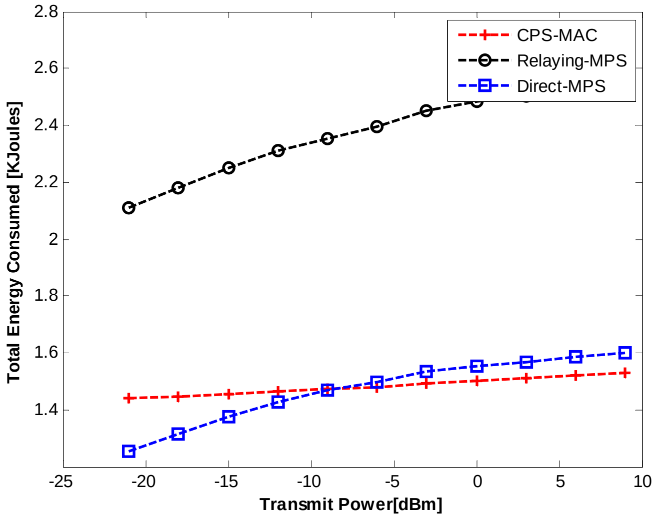


FIGURE 3.11: Total Energy Consumed

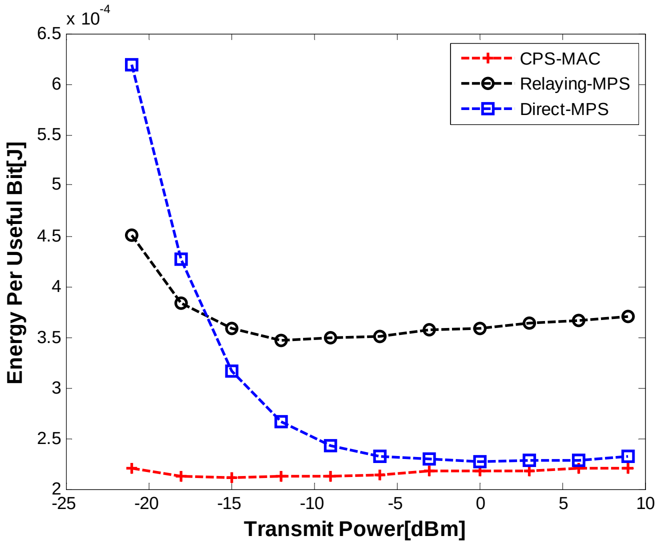


FIGURE 3.12: Energy Per useful bit

CPS-MAC-without-cooperation shows the performance of CPS-MAC in absence of cooperation. The difference in PER between CPS-MAC and CPS-MAC-without-cooperation represents the diversity gain achieved by using MRC for data packets. We see that for almost all transmission powers, combining is able to recover some packets resulting in a smaller PER for CPS-MAC. This means that there are always packets for which the direct and relayed transmission fails; however, their recovery is possible using combining. The total energy consumed by the whole network for the entire simulation duration is shown in Figure 3.11. The energy consumption of CPS-MAC is comparable to direct-MPS and significantly less then relaying-MPS. This is because CPS-MAC is able to wake

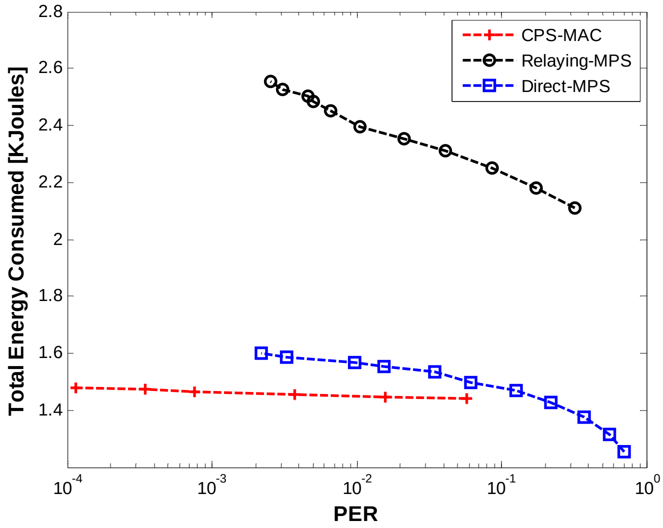


FIGURE 3.13: Total Energy Consumed vs Packet Error Rate tradeoff

up the 2-hop destination nodes in a single transmission cycle using repeated preambles from the 1-hop partner node. As the amount of time for waking up the node is significantly larger than the data transmission phase, size and number of preambles is a primary factor contributing to the energy expenditure. By reducing both the number of preambles sent and the time needed to wake up the nodes, CPS-MAC is able to reduce the energy utilization, making it comparable to direct-MPS.

Figure 3.12 shows the energy consumed per useful bit (EPUB) for the three configurations. The EPUB metric takes into account the energy consumption of all the nodes in the topology. For each node, its total energy is the sum of energy spent in transmit mode, receive mode, and sleep mode. For high transmission power, EPUB for CPS-MAC and direct-MPS is almost the same. However, at low transmission power, the improved PER pays off and CPS-MAC achieves significantly lower EPUB. Figure 3.13 shows the trade-off between total energy consumption and PER. For a given PER value, CPS-MAC consumes less energy then both direct-MPS and relaying-MPS. One thing to notice here is that direct-MPS is more energy-efficient at very low transmission power; however, the high PER value makes it infeasible for applications where better reliability is desired.

3.3.3 Results: Multihop Network

As discussed in Chapter 2, performance evaluation of cooperative protocols has been limited to either analytical results or a simple three-node scenario, comprising a single source-partner-destination setup. This is because, depending upon the protocol design under consideration, one or more additional functions would be required such as partner selection, cooperative addressing, packet combining, and three-way handshaking between source-partner-destination which are absent in conventional simulation and hardware platforms. Therefore, a three-node setup might not reflect the actual behavior of the protocols because factors such as channel contention and collisions are simply not present. In this section, we extend the performance evaluation of CPS-MAC to a multi-hop configuration where many sensor nodes are deployed around a sink to create a data gathering network. Such a multi-hop configuration allows us to examine CPS-MAC scalability properties. This also allows us to verify our results from the previous section. In the multi-hop configuration, all nodes generate traffic, which means CPS-MAC must efficiently handle channel contention, collisions, and idle listening.

Figure 3.14 shows the network topology. Here 17 sensor nodes are deployed around the sink. This number allows us to configure a network where nodes with varying degree of connectivity are present. Every node has between 2 and 8 connections with neighboring nodes. Furthermore, multiple network paths are available from the nodes to the sink.

As the network monitors physical or environmental conditions, such as temperature, pressure, or speed, nodes would periodically wake up, perform the sensing event and broadcast the data. This periodic traffic generation behavior is modeled at the application layer. All nodes generate data continuously at regular intervals, depending upon the frequency of a sensing event, except for the sink. This interval is defined using a simulation parameter and allows controlling the load the network is subjected to.

The performance of CPS-MAC is compared with relaying-MPS. In relaying-MPS, nodes simply relay each others' packets towards the sink and use preamble sampling [32] to wakeup neighboring nodes.The direct transmission case is not considered here because all the nodes will either be cooperating or relaying to deliver the packet to the sink.

We identify two parameters that can affect sensor node performance during operation. One is the power at which the sensor node transmits depending upon the desired transmission range, network lifetime requirement, and protocol design. For this, performance is evaluated for nodes operating at transmit powers in the range of -21dBm to 9dBm. The second parameter is the variation in load depending upon frequency of sensing events. For this, the network is subjected to different traffic loads by selecting precise intervals of 5min, 30s and 10s to generate a new application layer packet per node. These

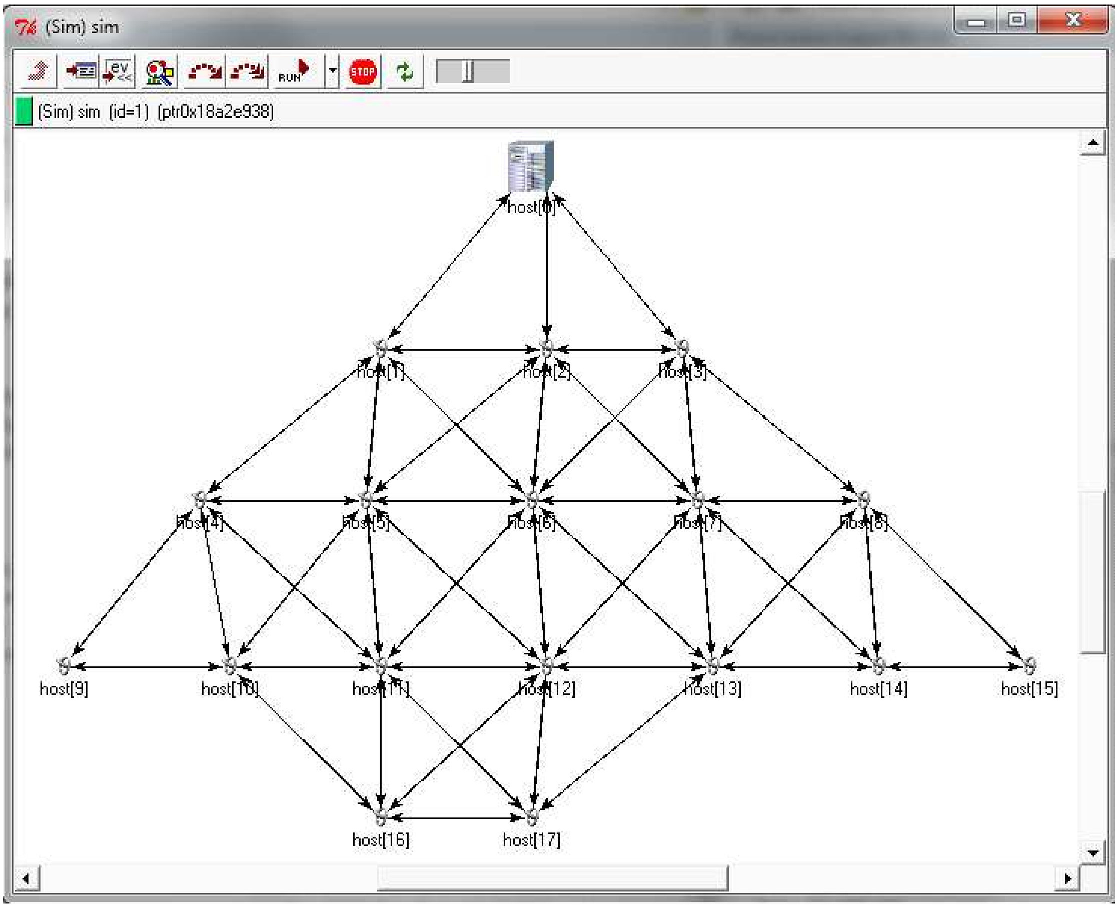
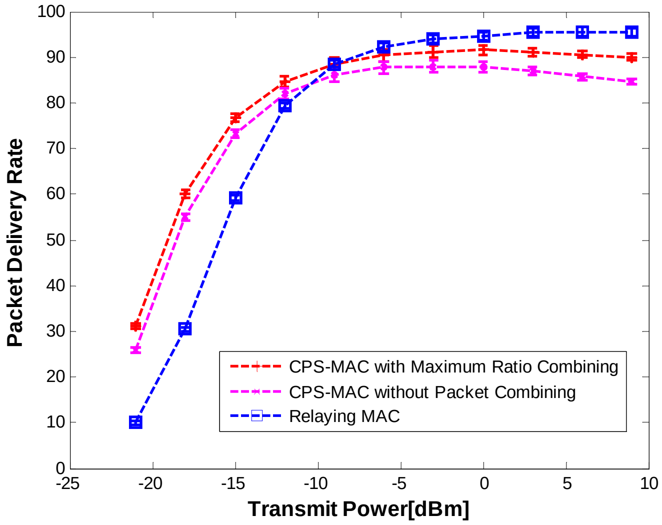


FIGURE 3.14: Network topology

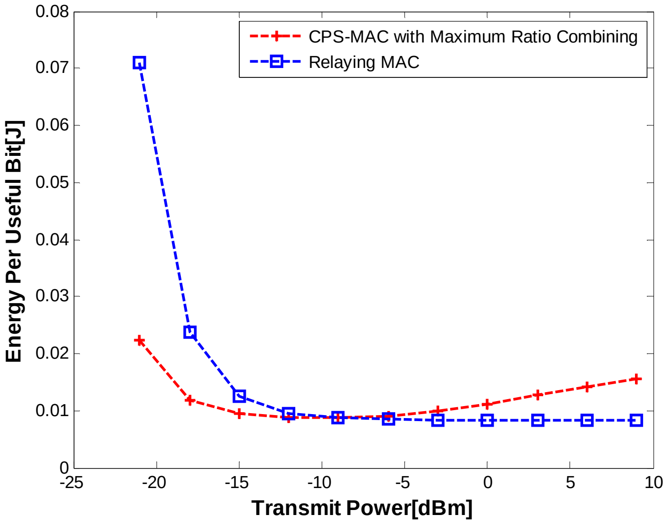
parameters are specified when the network is initialized and remain constant through the simulation run.

We primarily focus on evaluating the reliability and corresponding energy consumption of the network. In Figures 3.15, 3.16, and 3.17, reliability is represented as packet delivery rate (PDR), which is the percentage of packets delivered at the sink, excluding any duplicates. PDR is just a function of PER, which we used in the previous section to represent error rate for a single link, and is defined as 1-PER. In this section, we discuss the total throughput achieved by the entire network and prefer to use the PDR metric to represent it. MRC is used for packet combining at the destination and PDR results for CPS-MAC are plotted using both with and without packet combining. The difference represents the diversity gain achieved by MRC. Energy consumption is represented as energy per useful bit (EPUB) i.e., energy spent in transferring a payload bit from source node, through the network, to the sink.

Figure 3.16(a) shows that, under low traffic, CPS-MAC and relaying-MPS achieve comparable packet delivery rate (PDR). Nodes benefit from CC at low transmit powers



(a) Packet Delivery Rate

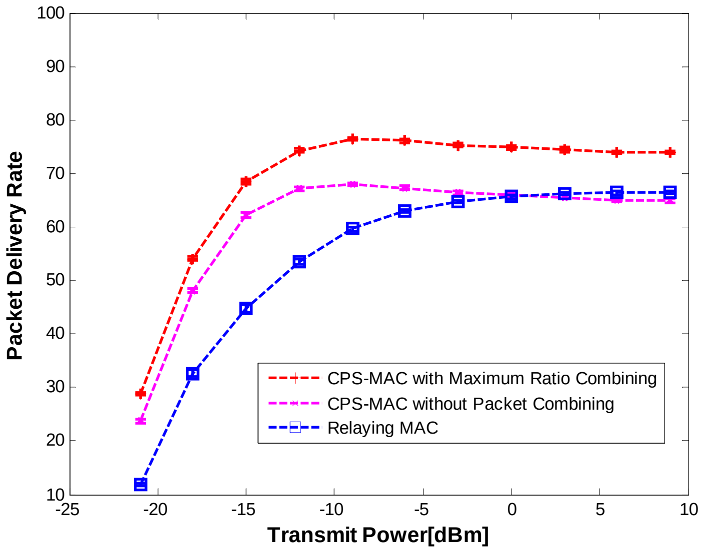


(b) Energy per useful bit

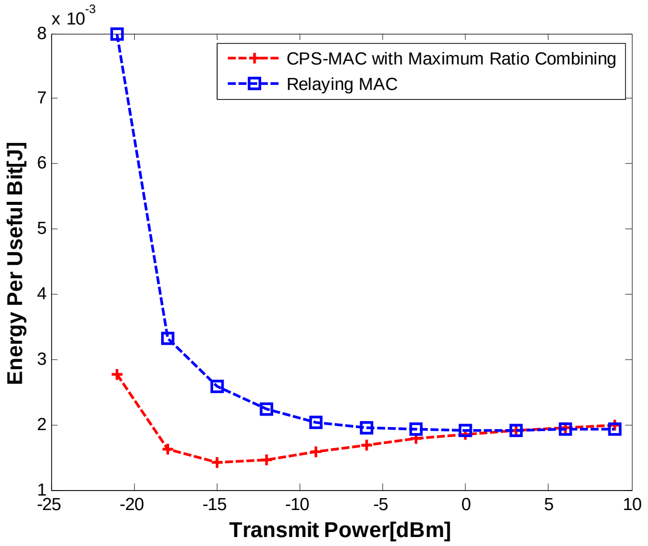
Figure 3.15: Traffic load of one packet generated every 5 minutes per node.

from -25dBm to -10dBm. However, when the transmit power is increased from -10dBm to 10dBm, the quality of 2-hop link improves accordingly, and relaying-MPS slightly outperforms CPS-MAC because of the latter's cooperation overhead.

The effect of increasing the traffic load can be seen in Figures 3.16(a) and 3.17(a). Here, CPS-MAC achieves better performance in almost all cases. This performance improvement over relaying-MPS is attributed to CPS-MAC's wake up scheme and CC over 2 hops. Repeating the preamble from the partner node increases the chances of the destination node waking up prior to data transmission. Cooperation over 2 hops means data can travel longer distances in a single transmission, thus increasing network



(a) Packet Delivery Rate

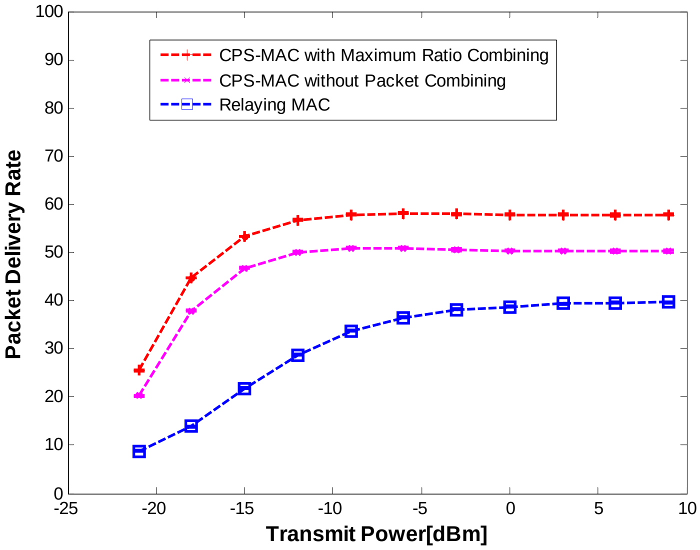


(b) Energy per useful bit

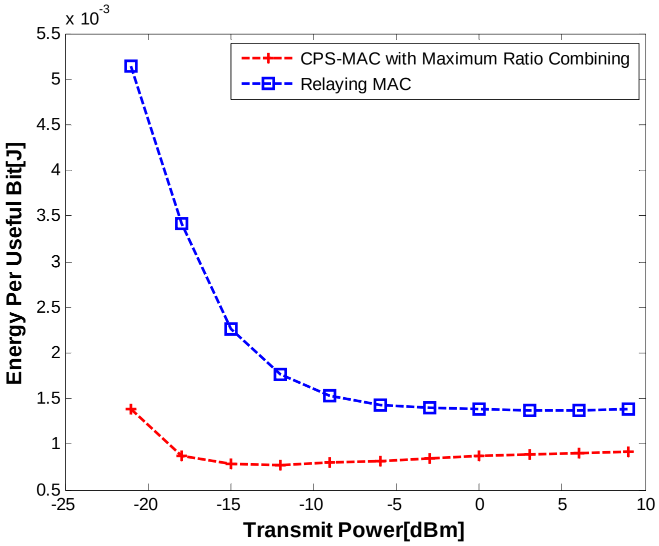
FIGURE 3.16: Traffic load of one packet generated every 30 seconds per node.

throughput, especially under heavy traffic load.

Figures 3.15(b), 3.16(b), and 3.17(b) show the energy consumed per useful bit (EPUB) for the three configurations. CPS-MAC's energy consumption corresponds to the PDR results. At high traffic load, the improved PDR pays off and CPS-MAC achieves significantly lower EPUB as shown in Figure 3.17(b). The next section discusses the distribution of energy consumption in the network.



(a) Packet Delivery Rate

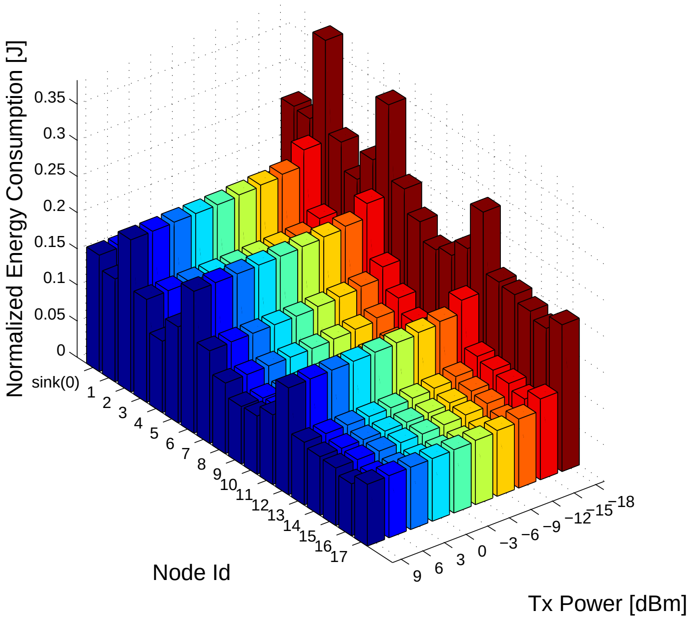


(b) Energy per useful bit

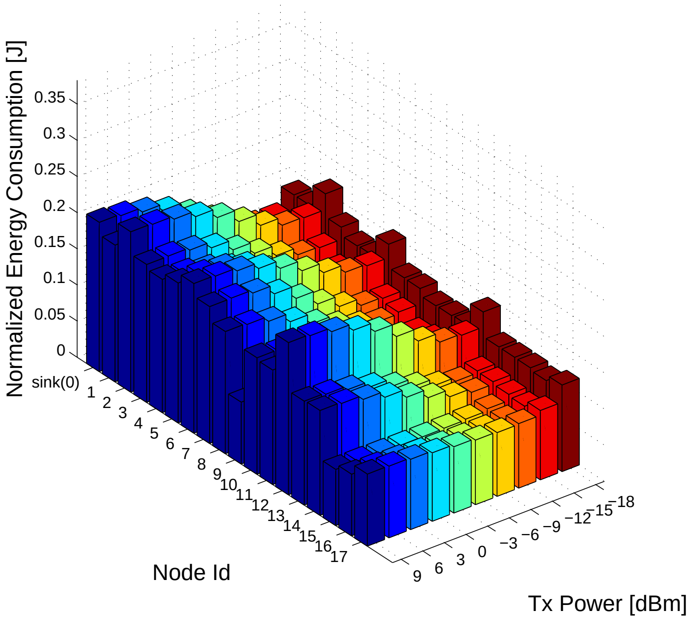
Figure 3.17: Traffic load of one packet generated every 10 seconds per node.

3.3.4 Energy Distribution in a Multihop Network

As multiple nodes are involved in cooperative communication, the task of forwarding data is divided among many nodes. This behavior can possibly spread-out the energy usage across the network more uniformly resulting in a graceful degradation of an energy-constrained network. This sections discusses this aspect and shows how CPS-MAC and Relaying-MPS distributes the energy usage for nodes in the network shown in Figure 3.14. The distribution corresponds to the performance results and the corresponding PDR and EPUB values discussed in Section 3.3.3. The energy usage of nodes in the



(a) Distribution of energy usage for Relaying-MPS

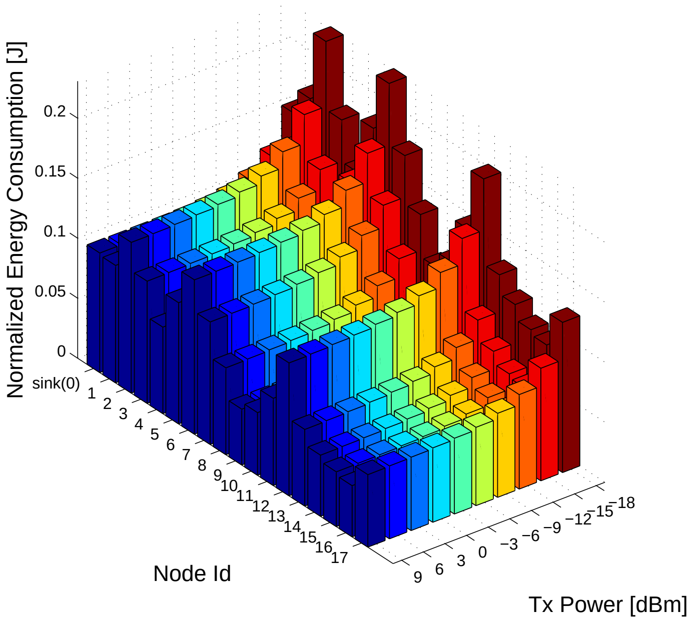


(b) Distribution of energy usage for CPS-MAC

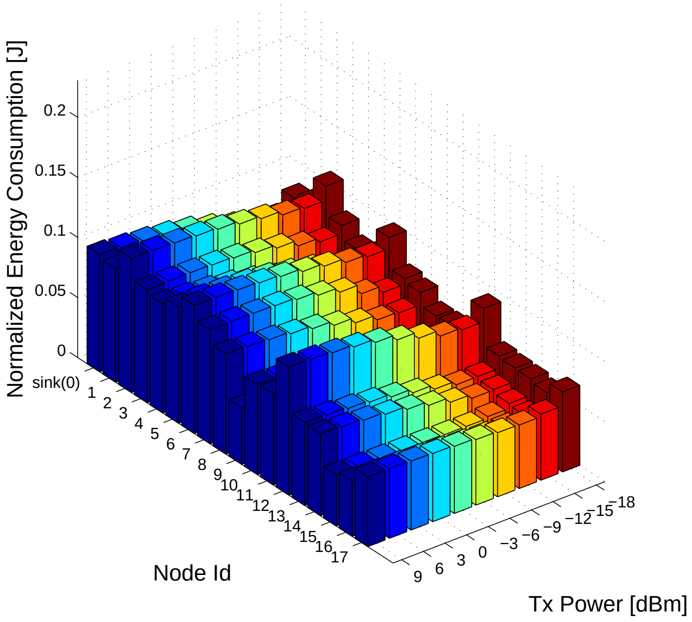
FIGURE 3.18: Traffic load of one packet generated every 60 seconds per node

network is normalized over the total number of packets delivered by the network to the sink, which is the work done by the network. This is useful because the absolute energy consumption values would not take into account the amount of work done by the network and therefore possibly give incorrect results by favoring a protocol with low energy usage but that does little or no useful work.

The results are discussed for the cases when the network is subjected to traffic loads



(a) Distribution of energy usage for Relaying-MPS



(b) Distribution of energy usage for CPS-MAC

FIGURE 3.19: Traffic load of one packet generated every 30 seconds per node

of one new application layer packer per node every 60 seconds, 30 seconds and 10 seconds, . In each figure, node's individual normalized energy usage is plotted against the transmission power and the Node Id.

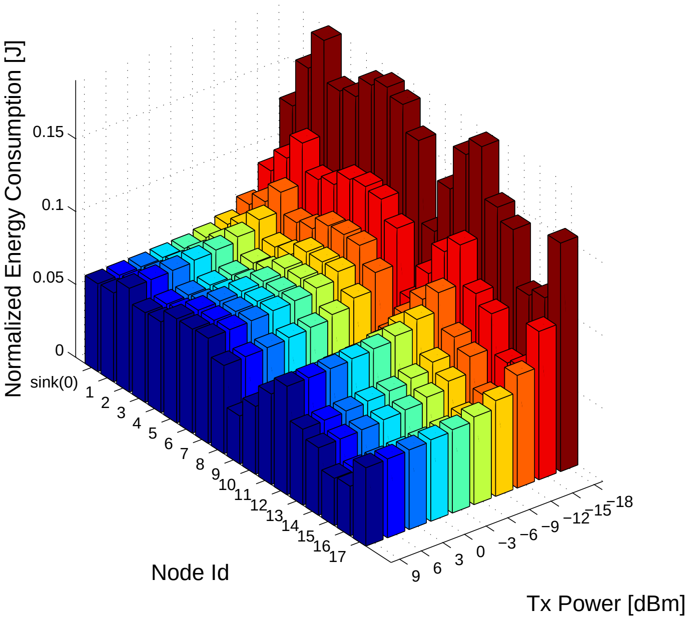
Figure 3.18 shows that the energy usage for both CPS-MAC and Relaying-MPS is highest for nodes 2, 6, and 12.

These nodes are at the center of the network and have the highest number of connecting edges from neighboring nodes. In Relaying-MPS, these 3 nodes use a fairly high amount of energy as compared to other nodes as shown in Figure 3.18. Also, the normalized energy usage increases as the transmission power decreases because of the reduction in amount of useful work done. This is particularly noticeable for relaying-MPS at Tx Power of -18 dBm in Figure 3.18. In contrast, CPS-MAC in Figure 3.18(b) has a more uniform distribution of energy consumption with nodes 2, 6, and 12 using a slightly higher amount of energy compared to neighboring nodes. Furthermore, in CPS-MAC the energy usage tends to increase with transmission power as nodes suffer from additional noise and interference caused by cooperative handshakes. At low transmission power, nodes benefit from cooperation resulting in more useful work and better energy usage. As the network is subjected to higher load of one packet per node every 30 seconds, shown in Figure 3.19, relaying-MPS distributes energy much like the previous case with the center nodes 2, 6, and 12 having a disproportionate usage as compared to other nodes. Although these three nodes also have higher energy usage in CPS-MAC as well, the difference is significantly less and the distribution within the nodes and across tx-power is more uniform. As the load is further increased to one packet per node every 10 seconds, shown in Figure 3.20, the energy usage shows some spreading out for relaying-MPS at higher transmission powers. At low transmission powers of -15 and -18 dBm, the energy usage is again high because of less useful work done. However, for CPS-MAC the energy usage spreads out very uniformly across all nodes. This is because the task of forwarding spreads out among all the nodes in the network. This mutual cooperation also results in better performance under heavy load as discussed in Section 3.3.3.

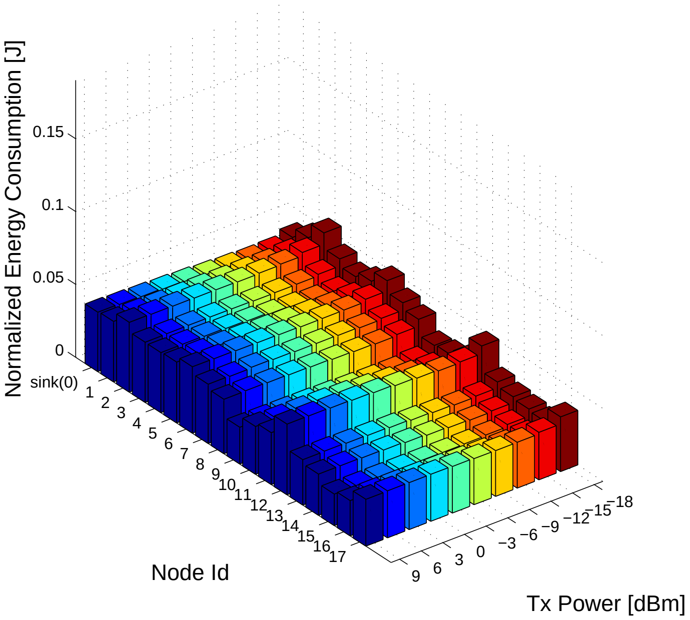
3.4 Summary

In this chapter, we showed the possible benefits of using cooperative communication to increase the reliability and to reduce energy consumption in WSNs. We propose CPS-MAC, which improves reliability by using overhearing to its advantage. The improvement is realized by forming cooperative triangles in densely deployed WSN where channel errors, collisions, idle listening, and overhearing significantly affect the performance.

We observe that, in duty-cycling MAC protocols for WSNs, the wakeup scheme has a big effect on the packet error rate at the destination. Repeating the preamble in a cooperative manner significantly increases the probability of the destination waking



(a) Distribution of energy usage for Relaying-MPS



(b) Distribution of energy usage for CPS-MAC

FIGURE 3.20: Traffic load of one packet generated every 10 seconds per node

up prior to data transmission. Results show that the destination is better able to receive and decode packets under this scheme compared to conventional MPS protocols. Furthermore, CPS-MAC delivers multiple copies of packet to the destination. Packet combining using MRC allows CPS-MAC to decode erroneous packets, reducing the PER. By reducing the number of preambles and the time needed to wake up the nodes and transferring data over multiple hops, the network can spend significantly less energy. This behavior is important in preamble sampling MAC protocols as energy used in sending and receiving preambles is the dominant factor in such a protocol.

Simulation results show that energy expenditure of CPS-MAC is comparable to the direct-MPS protocol and outperforms relaying-MPS. When scaled to a larger multi-hop WSN, cooperative communication can help achieving comparable packet delivery rates at low traffic load but the maximum benefit is achieved when the network is operating under mild to very heavy traffic load. CPS-MAC also shows a better distribution of energy usage among nodes in the network compared to relaying nodes. This can be particularly advantageous for graceful degradation of energy-constrained sensor networks.

In the next chapter we present RCT-MAC where we extend CPS-MAC to include acknowledgments for data packets, cooperation on demand, and comparison with WSN protocols.

Chapter 4

Reliable Cooperative Transmission MAC

4.1 Introduction

In this chapter we present RCT-MAC which improves upon the limitations of CPS-MAC and verifies our conclusions derived in Chapter 3. It uses the cooperative preamble repetition concept of CPS-MAC and focuses on addressing the following important issues missing from existing cooperative MAC protocols for WSN discussed in Chapter 2.

1. *Cooperation on Demand*: RCT-MAC implements an implicit *cooperation on demand* concept, i.e., nodes cooperate only when needed. This prevents energy wastage and makes the energy efficiency competitive with non-cooperative protocols.

2. *Acknowledgments*: RCT-MAC, in contrast to our previous protocol CPS-MAC, uses acknowledgments for both preambles and data packets to minimize retransmissions and idle listening and to improve packet delivery. The resulting improvement in reliability also benefits energy consumption.

3. Existing work, discussed in Section 2.2, does not evaluate the performance of cooperative MAC for WSN against conventional WSN protocol, some of which are shown in Figure 1.3. Most of the protocols have been compared to a non-standard protocol under different sets of metrics and scales. To give a deeper insight into the performance of cooperative protocols vs. conventional protocols in WSN, we

compare the performance of RCT-MAC with the following three well known MAC protocols for WSN:

(a) BMAC, a contention-based protocol that uses preamble sampling and ACK packets [42];

(b) LMAC, a contention-free Time Division Multiple Access (TDMA) protocol with ACK packets [35, 42];

(c) IEEE 802.15.4, which uses both contention-based and contention-free transmission and acknowledgments [24, 48].

A brief introduction of these protocols was presented in Section 1.2.2. In this chapter, we evaluate these protocols along with RCT-MAC for reliability, energy efficiency, and load under varying transmission power. This allows us to identify reliability vs. energy tradeoffs and where each of these protocols is effective.

4. *Implemented in MiXiM*: RCT-MAC has been completely implemented in MiXiM, which is a modeling framework for fixed, wireless, and sensor networks. It is a successor of Mobility Framework for OMNeT++ [94] and offers improved and detailed models for physical layer, radio wave propagation, interference estimation, and radio transceiver power consumption.

4.2 RCT-MAC Design

RCT-MAC has been designed for mobile and vehicular networks where nodes frequently change their position. We assume that the routing layer is responsible for keeping track of network topology and providing addressing information regarding source, partner, and destination. This information can be gathered using link-state information from received packets or by periodically broadcasting control packets.

RCT-MAC is responsible for waking up the partner and destination nodes and for cooperative data transfer. Unlike CPS-MAC which always uses cooperation, RCT-MAC allows dynamic cooperation, i.e., it cooperates only when needed. All the packets including preambles, ACK, and data packets can be sent cooperatively. This dynamic cooperation is managed using carefully adjusted wait timers through which different packets are automatically assigned different transmission priorities. The length of the wait timers can either be small, medium, or long depending upon the nodes role in cooperation and upon the packet type. We first introduce these timers in Table 4.1 followed by the protocol design.

TABLE 4.1: Wait timer for dynamic cooperation

Node	**Timeout Name**	**Abbrv**	**Wait Timer Duration**
Source	Send Preamble	T_{SP}	Long
Source	Send Data	T_{SD}	Small
Parter	Repeat Preamble	T_{RP}	Medium
Parter	Repeat Preamble Ack	T_{RPA}	Long
Parter	Repeat Data	T_{RD}	Long
Parter	Repeat Data Ack	T_{RDA}	Small
Dest	Send Preamble Ack	T_{SPA}	Small
Dest	Send Data Ack	T_{SDA}	Medium

The first column is the node's role in cooperation. The second column identifies the kind of packet scheduled for transmission by the node. Abbreviations, later used in the design figures, are in the third column. The last column *wait timer duration* identifies the length of time a packet will wait before being transmitted. This value is a percentage of the *awake duration* which is the amount of time nodes spent listening to the media between sleep cycles. In our evaluation, we define small, medium, and long as 5%, 20%, and 40% of the *awake duration.* The small duration of 5% translates to the minimal waiting time and therefore, the highest priority. The medium and long durations, used to determine if a preamble/data packet needs to be re-transmitted, have been carefully adjusted at 20% and 40% of *awake duration* to minimize unnecessary retransmissions and long waiting times. An additional random-backoff time is added to this wait timer to avoid simultaneous transmission by the nodes.

We discuss the protocol design in the next sections. In case of *cooperation on demand* using RCT-MAC, the nodes would either need no cooperation, partial cooperation, or full cooperation based upon the channel conditions between source, partner, and destination. In order to elaborate how the precise sequence of message exchanges varies, we show the working of the protocol under two different scenarios. In the first scenario, the channel conditions between source and destination are good and no cooperation should be required. In the second scenario, the channel conditions between source and destination are bad and full cooperation would be needed. A partial cooperation scenario would fall between these two scenarios. We assume that the source node has already selected and notified partner and destination nodes of its willingness to cooperate using a CPS-MAC-like or an alternative partner selection scheme [9–11].

In Section 4.2.3, we present the protocol design using state transition diagrams for the nodes when they are acting as source, partner, or destination.

4.2.1 Reliable channel conditions between source and destination

In this section, we show the working of the protocol when the channel between source and destination is reliable as shown in Figure 4.1.

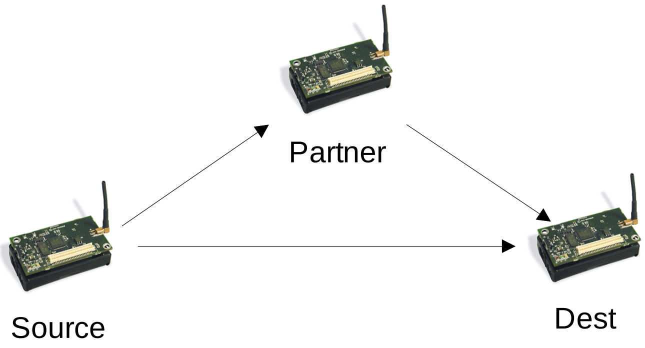


FIGURE 4.1: Channel condition between source and destination are reliable.

Here, the source initiates the handshake by sending out a *preamble*. The destination, on hearing the preamble, replies with a *preamble ack*. Although the partner also hears the *preamble* and will schedule T_{RP} to transmit a *repeat preamble*, the destination will have a higher transmission priority as T_{SPA} is less than T_{RP}. Similarly, the partner on hearing the *preamble ack* will schedule to repeat it but the source, upon hearing the ack, starts data transmission which again has a higher priority as T_{SD} is less than T_{RPA}. After receiving the data, the destination replies with a *data ack* which is always repeated by the partner. This implicit assigning of priorities allows only those packets to be repeated by the partner for which the direct communication was not successful or the corresponding acknowledgment was lost.

4.2.2 Unreliable channel condition between source and destination

To further elaborate *cooperation on demand*, we illustrate the scenario where the channel conditions between source and destination are not reliable; however, the channel conditions between source and partner, and partner and destination are reliable. This

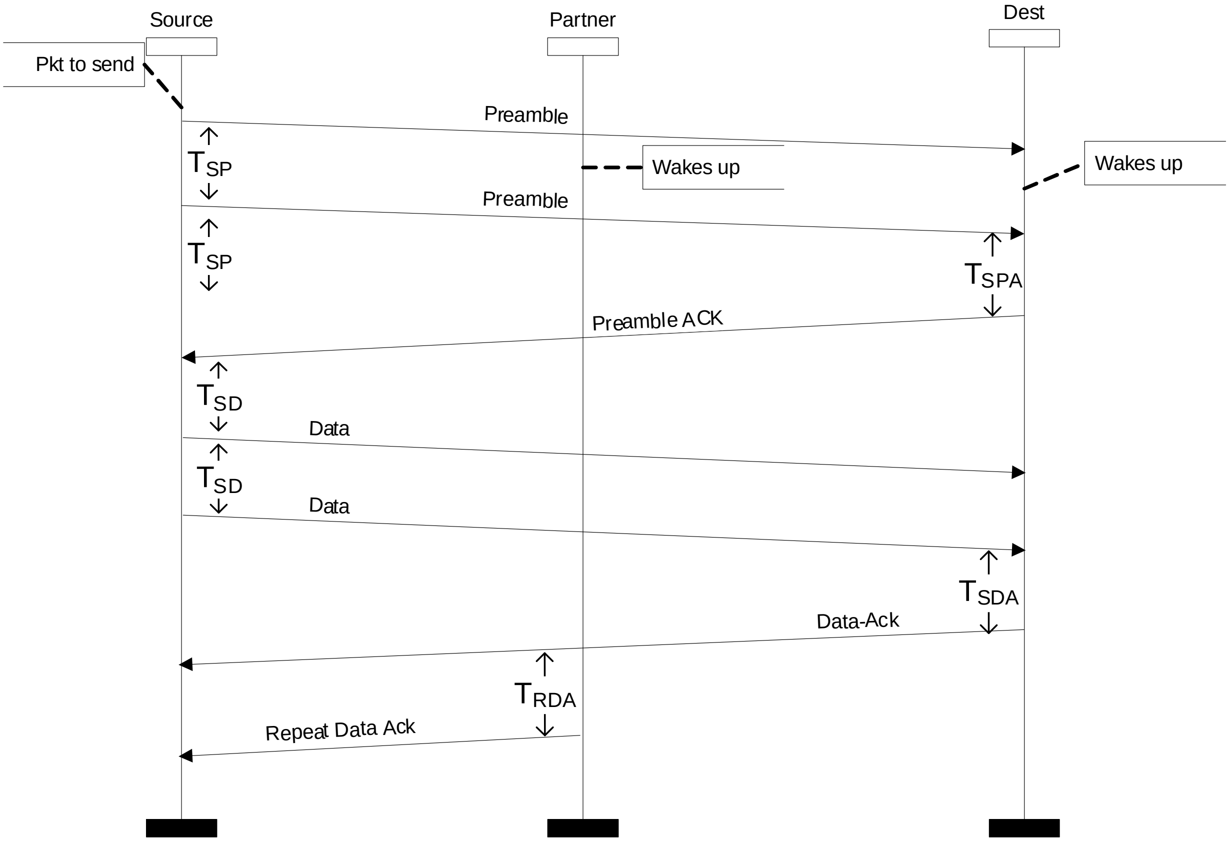


Figure 4.2: Message Exchange

means full cooperation from a partner is needed. Figure 4.3 shows the scenario. The message sequence chart is elaborated in Figure 4.4.

Here, the source starts by sending out a *preamble* and waits for a *Preamble ACK* from the destination before initiating the data transfer. The partner node, on hearing the preamble, schedules a wait timer T_{RP}. When the destination fails to reply and the T_{RP} expires, the partner starts sending the *Repeat Preamble* packet. This preamble repetition improves the chances of waking up the destination. The partner continues repeating preambles until one of the following event occurs: It hears a *Preamble ACK*, a max-retries limit is reached, or a wake-up timeout triggers, which puts it into sleep mode thus discarding the handshake session and preventing drainage of energy, incase the destination fails to respond. When the destination hears either the *Preamble* or *Repeat preamble* it replies with a *Preamble Ack* which has a higher transmission priority because the duration of T_{SPA} is less then the duration of T_{RP} and T_{SP}. This ack is then repeated by the partner. The source node, on receiving the *Preamble Ack*, starts sending out the *Data* packets buffered in the queue. The partner upon receiving the first data packet

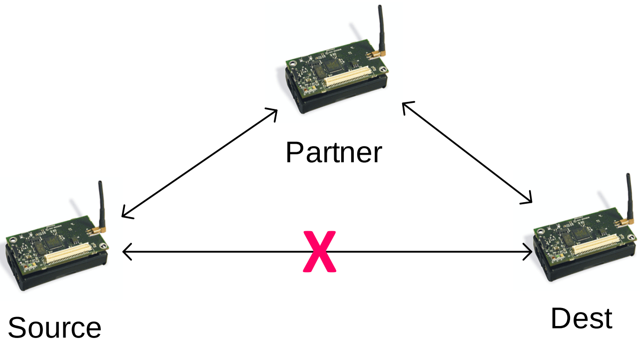


FIGURE 4.3: Channel condition between source and destination are not reliable.

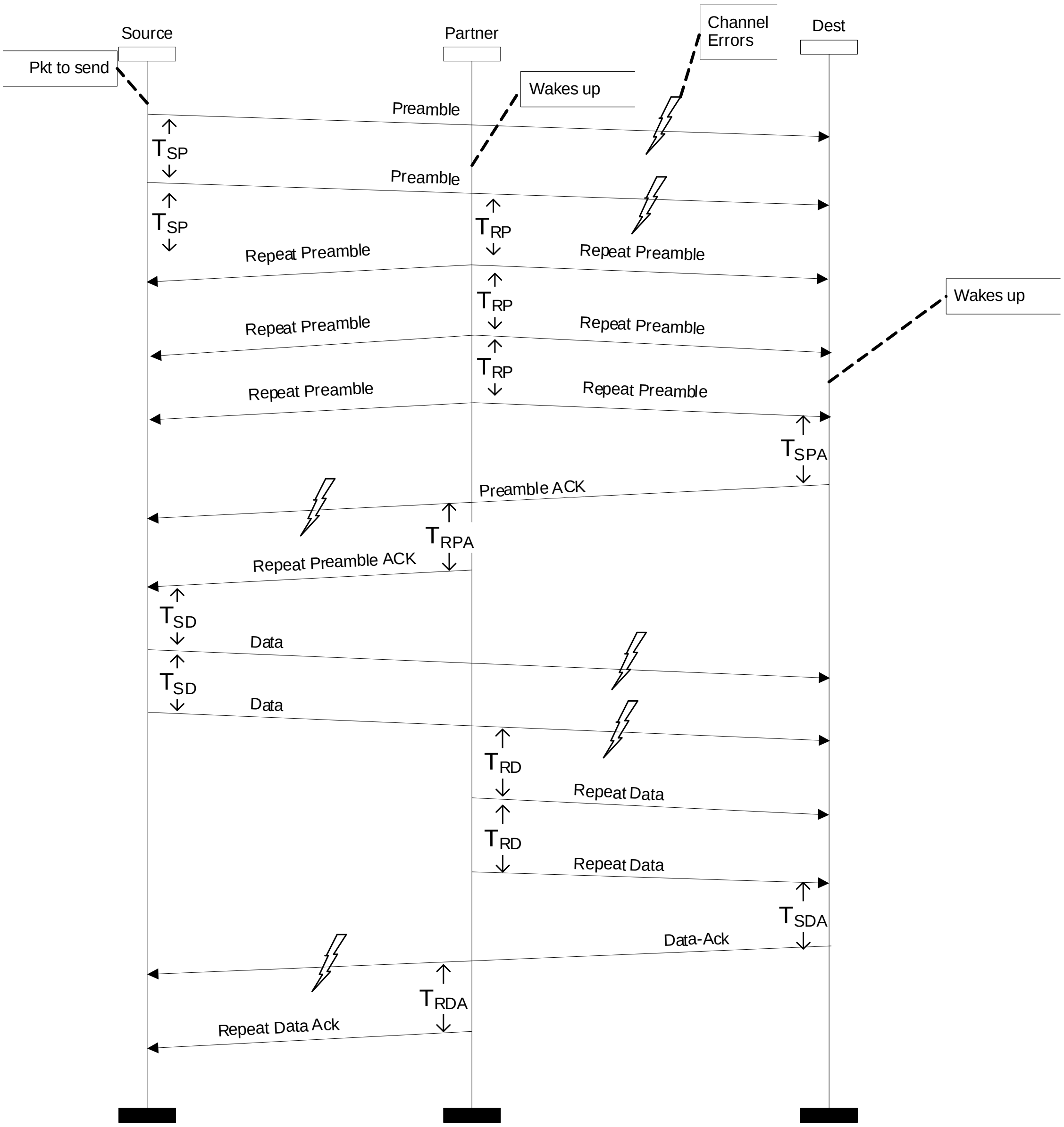


FIGURE 4.4: Message Exchange

schedules the T_{RD} for retransmission. However, as the duration of T_{RD} is long compared to source's T_{SD}, the source will timeout first and send the next data packet in its queue before the partner can transmit. The partner will reschedule its T_{RD} upon receiving a new data packet from the source. Eventually, T_{RD} will timeout and the partner will repeat the *Data* packets. Following this, the destination will reply with a *Data-Ack*. This ack serves as the cumulative ack for all data packets. The *Data Ack* is always repeated by the partner. This is because unnecessary cooperative transmission by the partner are preempted by following packets from source and destination; however, in case of *Data Ack* there is no packet following it. This additional redundancy, additionally, introduces robustness against cases where the *Data Ack* might be lost. In case the destination receives redundant packets, they are filtered using sequence numbers. Following this, all nodes wait for a listen interval before going to sleep.

4.2.3 State Transition Diagrams

For readers interested in the detailed functioning of RCT-MAC, we present the state transition diagrams in Figures 4.5, 4.6, and 4.7 where nodes are acting as source, and partner, and destination respectively.

4.3 Simulation Setup

RCT-MAC has been implemented in MiXiM [95, 96]. It allows wireless and mobile network simulations using the OMNeT++ Network Simulator (OMNeT++).

We compare the performance of RCT-MAC with conventional MAC protocols for WSN namely BMAC, LMAC, and IEEE 802.15.4 MAC [42, 42, 48]. An introduction to these protocols was presented in Section 1.2.2. We consider a three node network where nodes are mobile and move at a constant speed of two m/s randomly and independently of each other. A three node network allows us to use a simple routing layer for all the protocols, with pre-initialized node roles as source, partner, and destination. This is needed because RCT-MAC has been developed with the intent of investigating the *cooperation on demand* idea and does not incorporate a partner selection scheme. A partner selection scheme, similar to CPS-MAC, will need to flood the network repeatedly in a larger network. This can cause significant overhead, especially in mobile networks, as discussed in Section 3.3.

In the Table 4.2, we list the simulation parameters used for our evaluation.

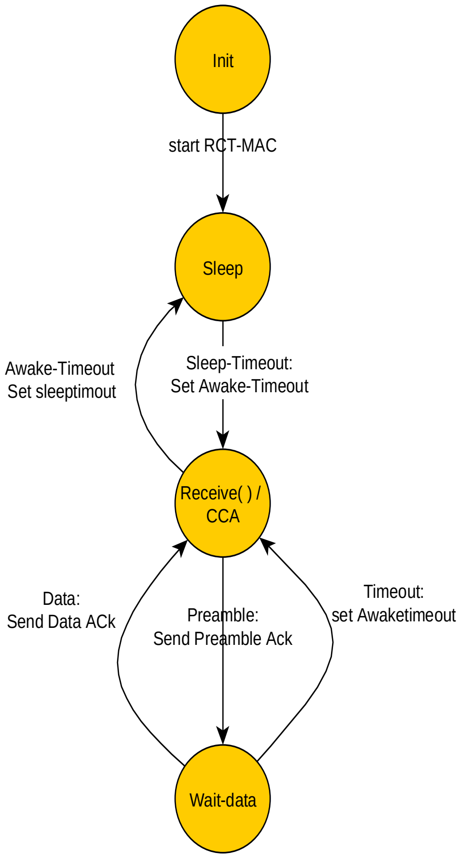


FIGURE 4.5: RCT-MAC: State Transition Diagram for Destination Node

TABLE 4.2: Fixed Simulation Parameters for Performance Evaluation

Parameter	
Carrier Frequency	2.4Ghz
Path loss Coefficient	3
Fading Model	Rayleigh Fading
MAC Queue Length	25
Packet Length	60 Bytes
Bit Rate	15 kbps
MAC Acknowledgments	Yes
Battery Voltage	3.3 V
Mobility	Yes
Mobility Speed (m/s)	2
Traffic Generation	Periodic

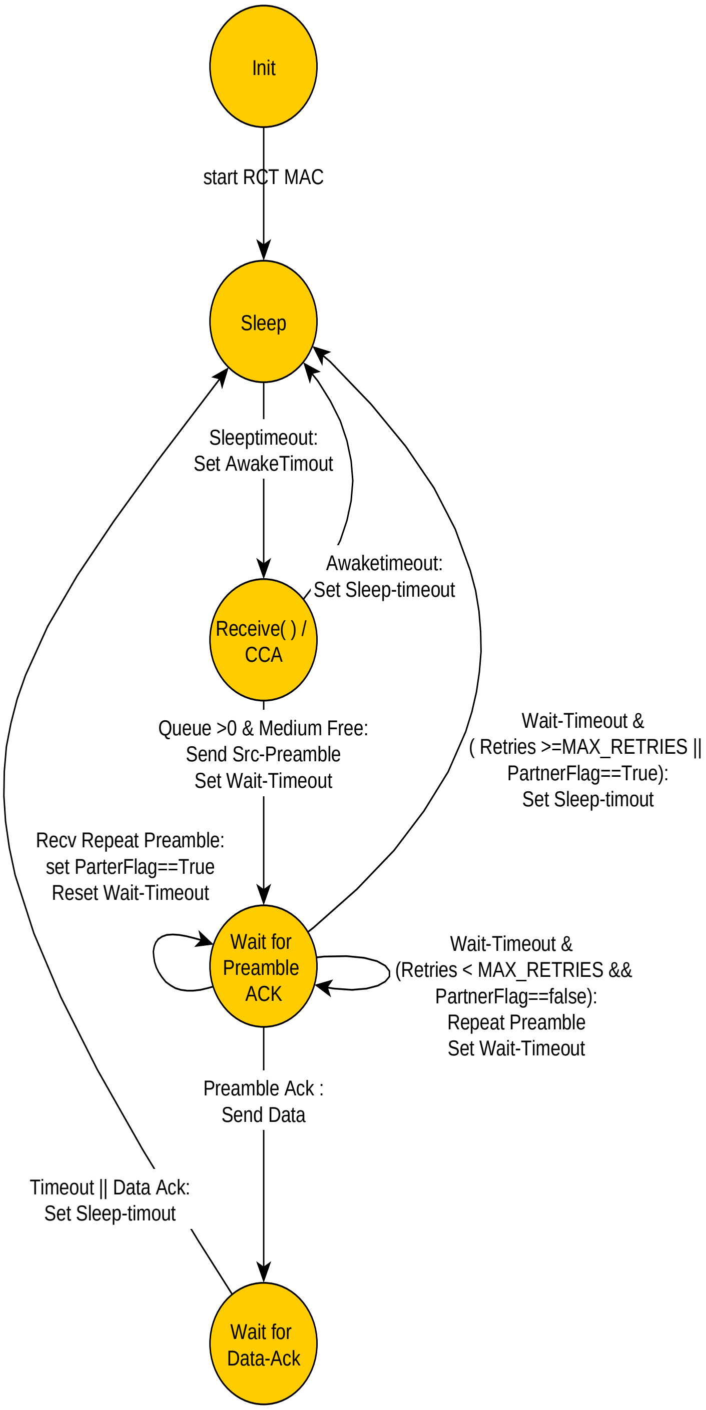


FIGURE 4.6: RCT-MAC: State Transition Diagram for Source Node

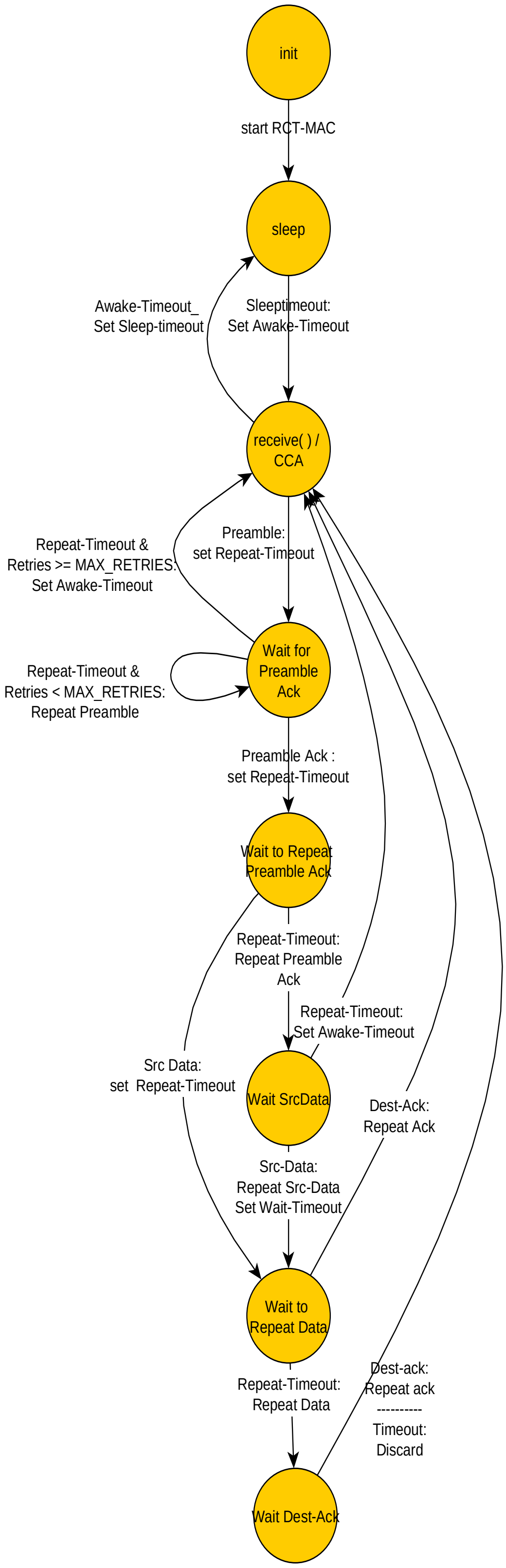


Figure 4.7: RCT-MAC: State Transition Diagram for Partner Node

The performance is evaluated by varying transmission power and traffic load. The traffic load is defined as *Inter-packet generation interval* which is the exact time in seconds a node waits before generating a new packet. The transmission power is expressed in milli-Watts (mW). The values are presented in Table 4.3.

Table 4.3: Variable Parameters for Performance Evaluation

Transmission Power(mW)	1	4	8	12	16	20	-
Inter-packet generation interval (s)	0.1	0.5	1	1.5	2	3	4

Next we present the results obtained from the performance evaluation of RCT-MAC.

4.4 Evaluation

We focus on evaluating performance in terms of PDR and energy efficiency. Figures 4.8 to 4.20 show the PDR and energy efficiency of the protocols when traffic load is increased based on the *Inter-packet generation interval.*

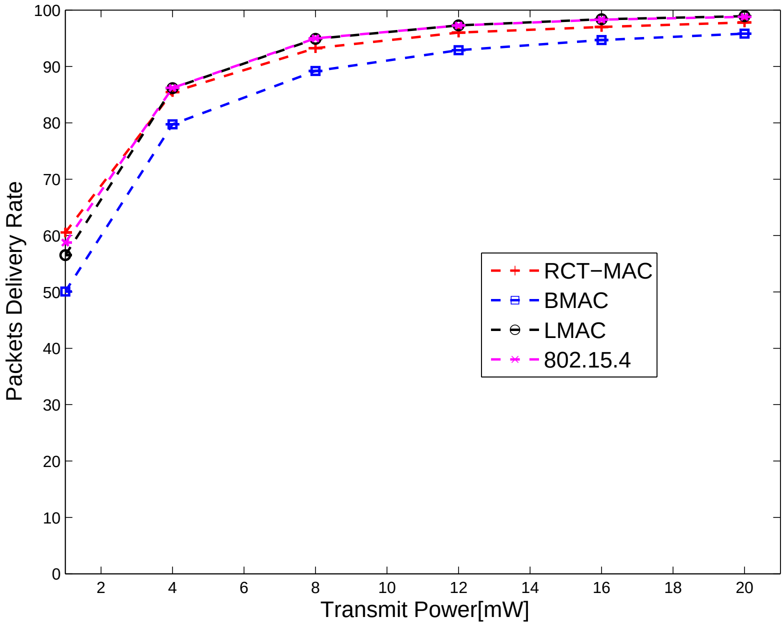


Figure 4.8: Packet Delivery Rate for 1 packet every 4s

Figures 4.8 and 4.9 show the result when the network is subjected to a low traffic load of 1 packet every 4s. The first figure shows the PDR and the second EPUB. We see that almost all the protocols have similar delivery rate with BMAC having a slightly lower PDR. This means that both contention-based and time-division based schemes handle low traffic load equally well. However, we see a contrast in EPUB where

LMAC uses significantly lower energy followed by RCT-MAC. This is because LMAC is a TDMA-based protocol and, unlike other protocols, does not needs a wakeup scheme or handshaking prior to transmission.

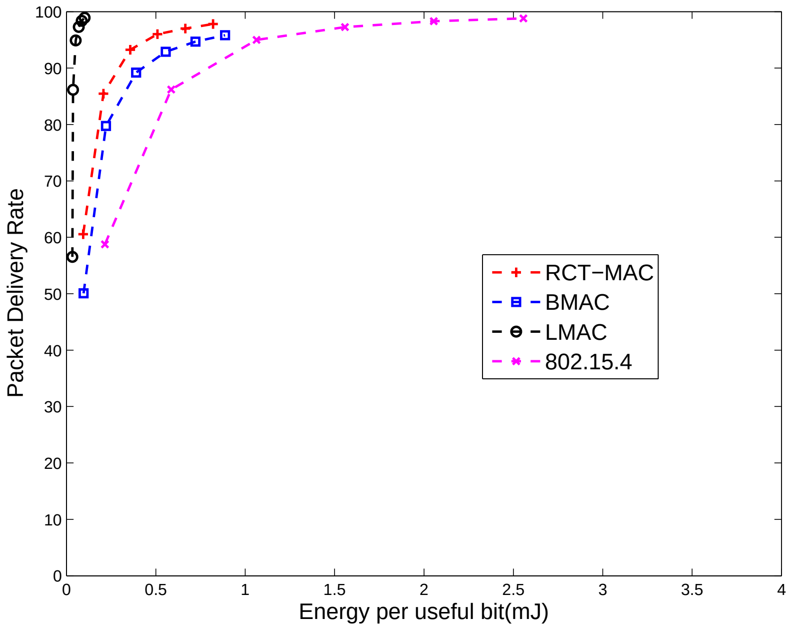


FIGURE 4.9: PER vs EPUB for 1 packet every 4s

Figures 4.10 and 4.11 show the PDR and EPUB for a traffic load of 1 packet every 3s, respectively. We see that there is no significant difference in the performance of the protocols as compared to the previous case. We consider this the boundary line load value below which the PDR of the protocols does not show any significant difference.

As we increase the traffic load to 1 packet every 2s, we see that the performance of LMAC and BMAC deteriorates. This is because LMAC, being a TDMA protocol, has a fixed number of time slots which cannot adapt to the changing traffic load. BMAC is limited by its preamble which is fixed in length and thus unable to adapt to the high traffic. RCT-MAC uses acknowledgments during the handshake which allows it to minimize the time spent in handshaking and waking up the neighboring nodes. IEEE 802.15.4 also achieves a high PDR; however, it uses significantly more energy compared to RCT-MAC. For protocols with a lower reliability requirement, LMAC can be used but for high reliability requirements, RCT-MAC is the most suitable.

Further increasing the traffic load to 1 packet every 1.5s, we see a deterioration in the performance of BMAC and LMAC. For LMAC, its TDMA behavior tends to consume a constant amount of energy regardless of the load; however, it drops a significant amount of packets which negatively affects its performance. This is because LMAC, by design,

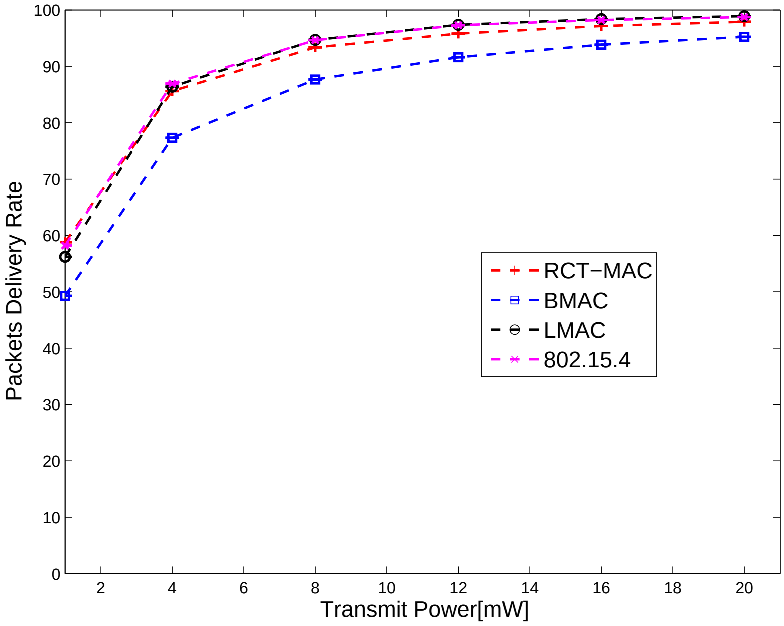


FIGURE 4.10: Packet Delivery Rate for 1 packet every 3s

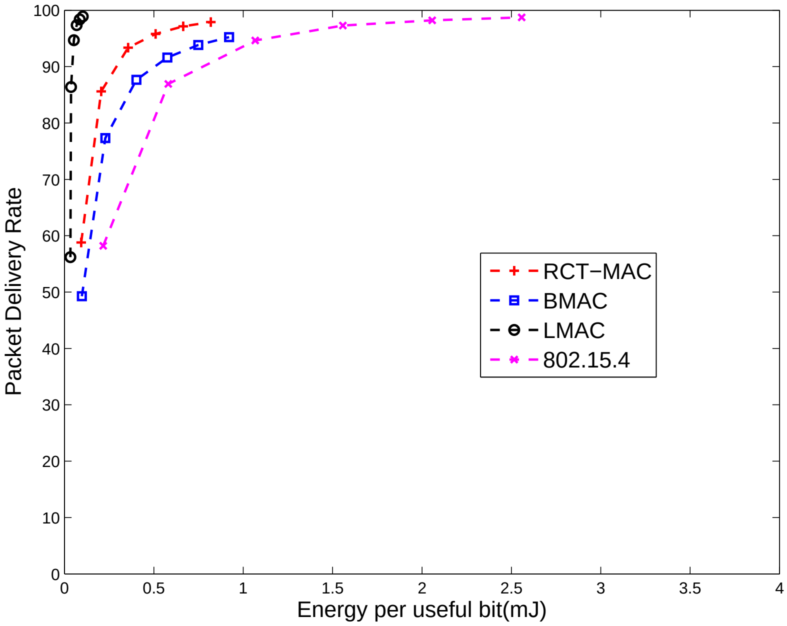


FIGURE 4.11: PER vs EPUB for 1 packet every 3s

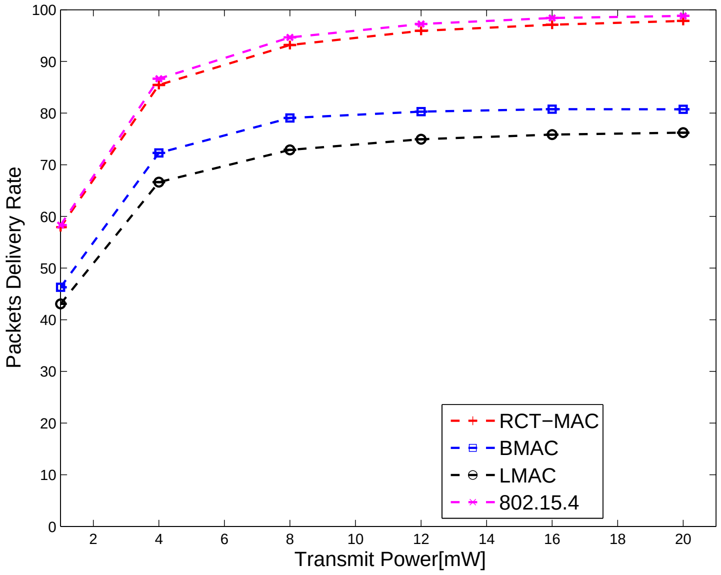


FIGURE 4.12: Packet Delivery Rate for 1 packet every 2s

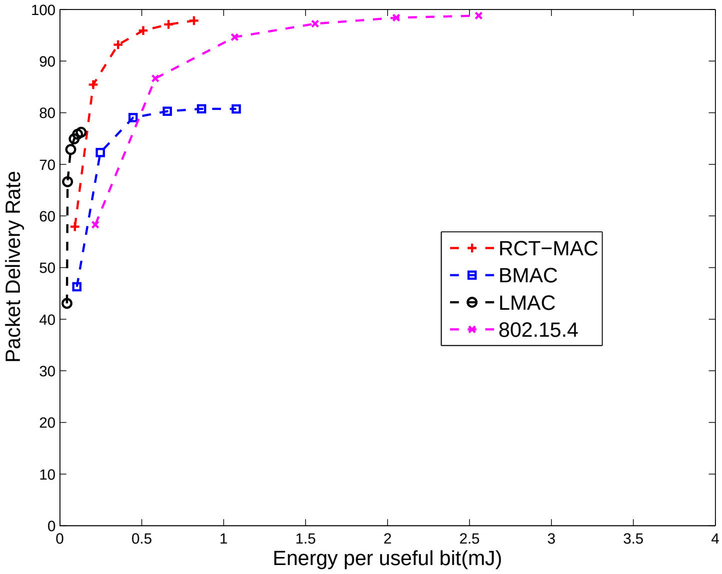


FIGURE 4.13: PER vs EPUB for 1 packet every 2s

limits one node to use only a single slot in a frame [34]. This prevents LMAC from scaling according to traffic load, resulting in wasted slots in a frame and overflowing queue. This also explains the LMAC ability to use a constant amount of energy regardless of the load.

BMAC again spends a considerable amount of time in handshaking and forwarding the data in a hop-by-hop fashion. Both RCT-MAC and IEEE 802.15.4 show high PDR for high traffic load; however, RCT-MAC outperforms all protocols in terms of EPUB.

For even higher traffic load of 1 packet every 1s, the performance of BMAC and LMAC

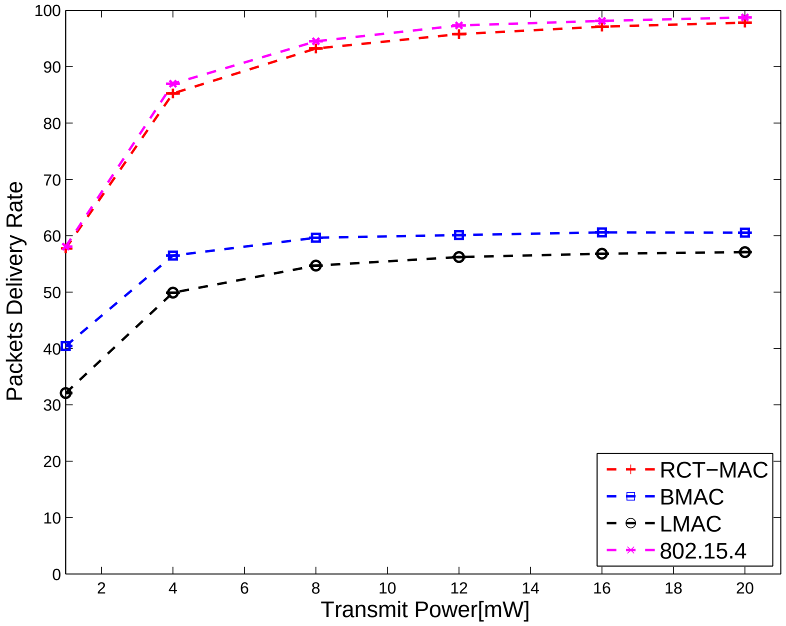


FIGURE 4.14: Packet Delivery Rate for 1 packet every 1.5s

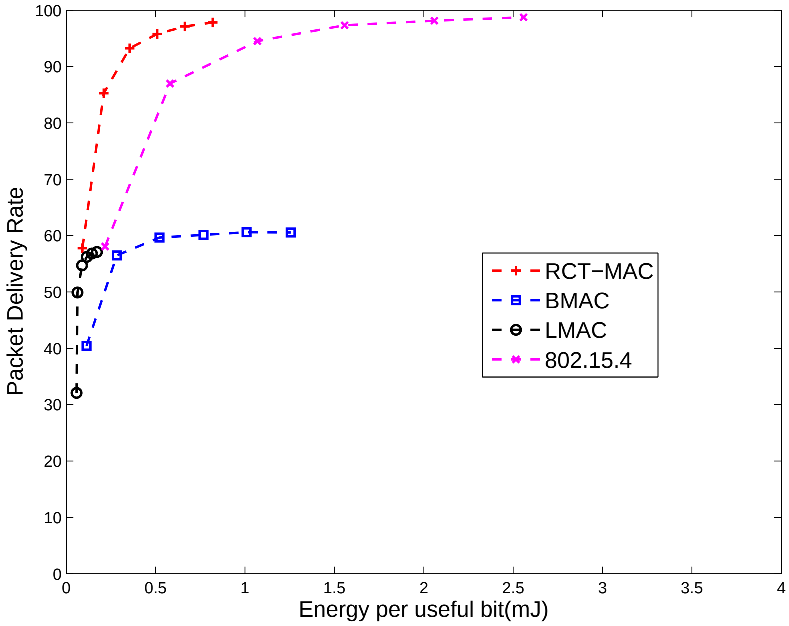


FIGURE 4.15: PER vs EPUB for 1 packet every 1.5s

further deteriorates with PDR going down to just 40%. RCT-MAC and IEEE 802.15.4 still achieve a very high PDR with RCT-MAC outperforming IEEE 802.15.4 in energy efficiency.

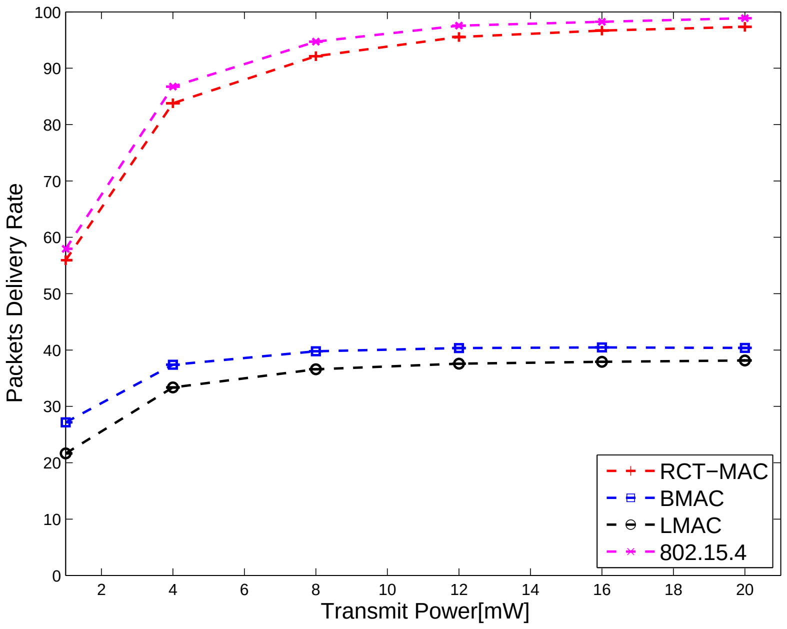


FIGURE 4.16: Packet Delivery Rate for 1 packet every 1s

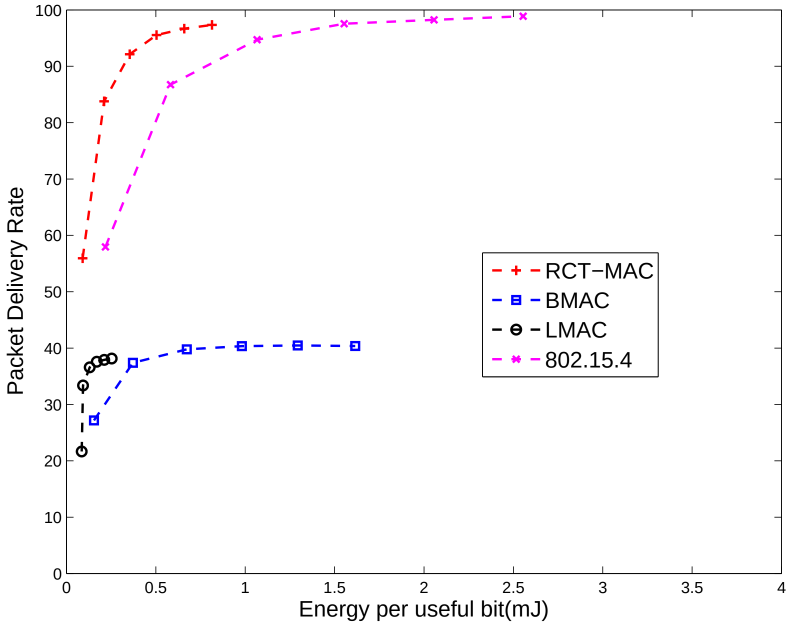


FIGURE 4.17: PER vs EPUB for 1 packet every 1s

For a traffic load of 1 packet every 500ms, i.e., 2 packets every one second, the PDR of BMAC and LMAC drops further down to approximately 20% and 15% respectively. RCT-MAC shows a slight decrease in performance but still performs better than IEEE 802.15.4 in terms of energy efficiency.

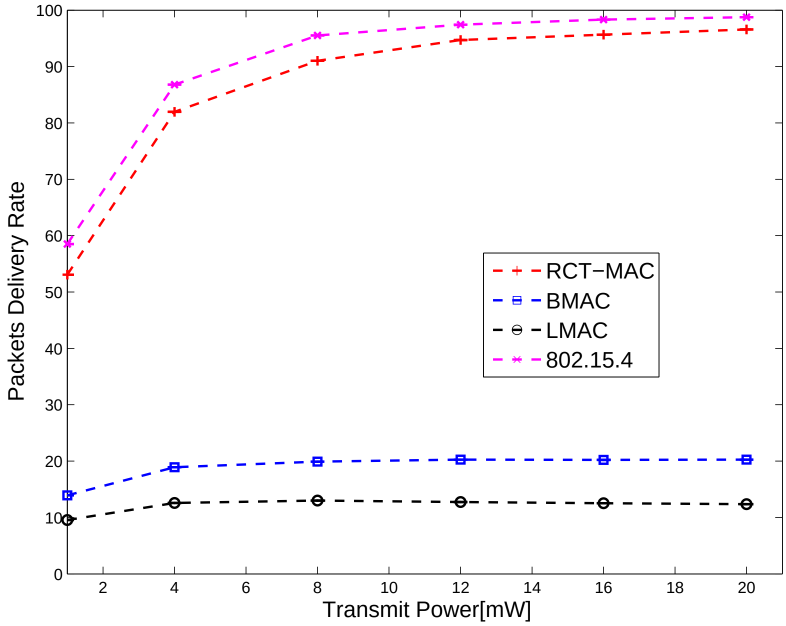


FIGURE 4.18: Packet Delivery Rate for 1 packet every 500ms

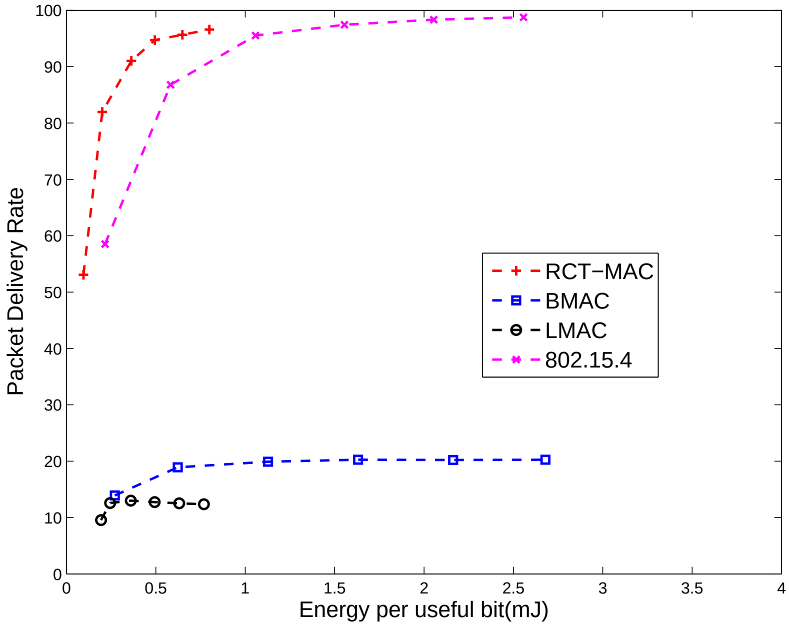


FIGURE 4.19: Packet Delivery Rate for 1 packet every 500ms

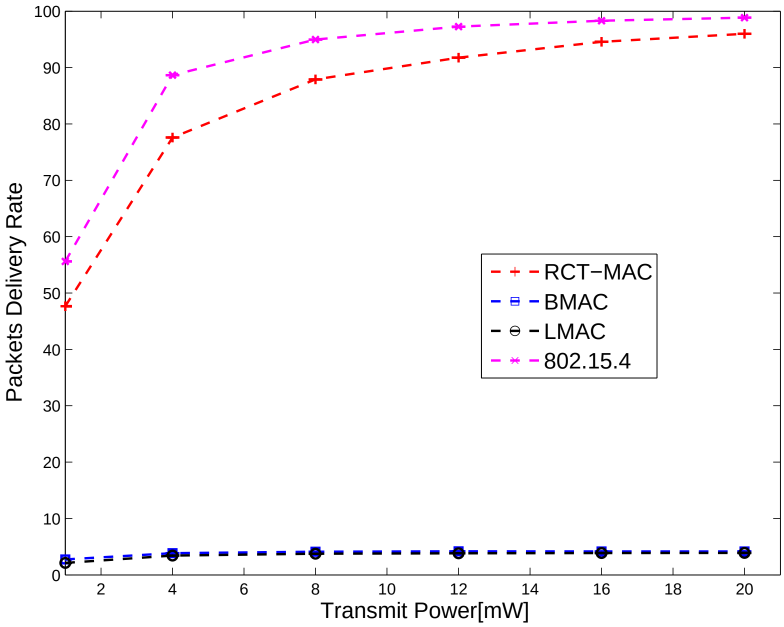


FIGURE 4.20: Packet Delivery Rate for 1 packet every 100ms

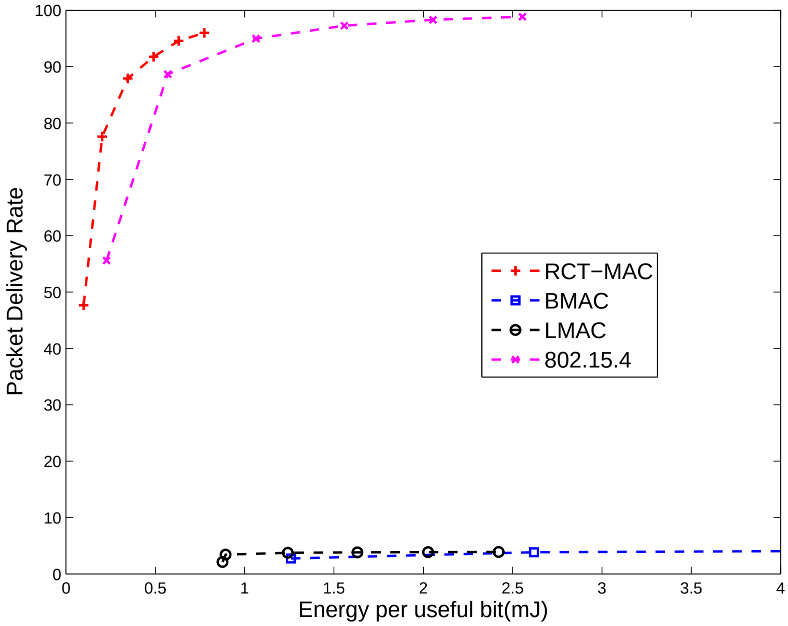


FIGURE 4.21: PER vs EPUB for 1 packet every 100ms

Finally, for a very high traffic load of 1 packet every 100ms, i.e., 10 packets per second, RCT-MAC performance drops slightly but sill achieves more than 95% PDR. The energy consumption of RCT-MAC compared to IEEE 802.15.4 for the same PDR values is lower thus giving a better energy vs. reliability tradeoff. LMAC and BMAC are unable to handle such high traffic load and continuously drop packets. As discussed earlier, LMAC limits nodes to use only one slot in a frame [34]. This means that nodes can deliver packets at a constant rate; however, they cannot use any free slots that might be available, in the case of increasing load. For LMAC to be most effective in such a high load scenario, we would ideally need to reduce the number of slots to one per frame. While this would help in a high load scenario, the nodes would then be wasting energy when operating under low traffic load, because they would always be awake and ready to transmit. This inflexibility means that, for LMAC to be most effective, the number of possible nodes and the traffic pattern should be carefully considered before deployment, and the number of slots accordingly adjusted. Analyzing the possibility of dynamic slot adjustment for TDMA protocol such as LMAC, depending upon offered load, and the implementation complexity involved is an interesting topic and will be considered in future studies.

4.5 Summary

In this chapter, we have presented RCT-MAC which uses cooperation on demand to improve energy efficiency in WSN. We compare the performance of RCT-MAC against traditional WSN protocols namely BMAC, LMAC, and IEEE 802.15.4. Results show that, for low traffic load, LMAC is suitable as it minimizes the contention in the network and therefore improves throughput. However, as the traffic load increases, the contention-based protocols are better able to adapt to this change. Performance of LMAC suffers because of its inability to adjust slot usage per frame depending upon the offered load. Overall, IEEE 802.15.4 achieves a better PDR. RCT-MAC performs significantly better than IEEE 802.15.4 in terms of energy efficiency which means that for a certain desired PDR value, RCT-MAC will be more energy-efficient. These results also verify our conclusion that the maximum benefit of cooperation is achieved when the network is operating under mild to very heavy traffic load.

Chapter 5

Packet Error Prediction Using Preamble Sampling

5.1 Introduction

Partner selection schemes are an important part of Cooperative Communication [9, 10]. A significant amount of work has been done in identifying partner nodes which can maximize the chances of successful retransmission. Protocols may use one or more metrics such as link quality indicator (LQI), received signal strength indication (RSSI), and routing layer information to identify a suitable partner node. Channel estimation schemes, based on LQI and RSSI, have received significant attention [9, 97–100]. However, recent work has shown that they are not sufficiently reliable in the case of low-power radio transceivers [101, 102].

In this chapter, we present an additional technique, particularly envisioned for preamble sampling-based cooperative protocols, which can be used to supplement the traditional metrics for partner selection. The idea is to predict the chances of a partner node receiving an erroneous packet from the source based on the previously received preamble packets. This is feasible because the source node sends a number of preambles to the neighboring nodes to wake them up during the handshake phase. In mobile networks, where a number of nodes could be potential partners and fading channel conditions exist, reception of erroneous preambles could indicate that the data packet could also be erroneous. Rajeswari et al. have done analytical work on estimating channel impulse response using preambles [103]. We, however, use experimental data to evaluate our idea. Gomez and Campbell have also presented a channel prediction scheme where RTS/CTS packets, in IEEE 802.11 PCF mode, are used as probes for channel estimation [104]. As discussed in Section 1.2.1, RTS/CTS packets are not part of the PCF mode which means that they pose an overhead. Preamble sampling protocols have the advantage that the preambles have to be transmitted anyways and the bit sequence in the preamble is already known to all the nodes. The following two scenarios exemplify cases where this prediction information can be used.

- For cooperative schemes where partner selection is done at the source, this information could be utilized by the MAC layer and communicated to the source node during the handshake phase, where it can be used by the source in selecting the partner with the highest probability of successful packet reception and therefore retransmission to destination. While this selection would be a node's best estimate, based on the gathered information, it might not actually be the optimal node to choose, especially in mobile networks where topology and channel conditions can quickly change.

- For cooperative schemes where partners must negotiate among themselves when an opportunity to retransmit exists, one possibility is to implement a backoff mechanism where potential partners calculate individual backoff timeout values using a probabilistic estimate of receiving a correct or incorrect packet based on previous receptions. Then, the node with the shortest timeout, and therefore highest probability, will retransmit first and the remaining nodes can decide to delay or abort their retransmission. Such a scheme assumes that all the potential partner nodes can hear each other, otherwise simultaneous transmissions will cause collisions at the destination. For the case where partners are not in transmission range of each other, a source or a destination-initiated partner selection scheme can be used.

In this chapter, we analyze the effectiveness of such an error prediction scheme by using data obtained from an experiment. We first explain the experimental setup in Section 5.2 and present the results in Section 5.3.

5.2 Setup

The idea is to send packets consisting of a predetermined bit sequence from a stationary sender to a moving receiver. These packets are checked at the receiver for transmission errors. The result is then analyzed for determining if correlation exists between consecutive packet errors, i.e., can an error in one packet, or a sequence of consecutive packets, provide information about probability of an error in a succeeding packet.

Our setup consists of one sender and one receiver node. The sender is picked from a grid of stationary sensor nodes mounted on the ceiling, shown in Figure 5.1. The receiver is moving and placed on the end of a rotor blade attached to a motor with a speed controller, shown in Figure 5.2. This allows us to incorporate movement and control the speed of the rotor blade. We repeat the experiment with the rotor running at 0.1Hz, 1.0Hz, 1.5Hz, and 3Hz.

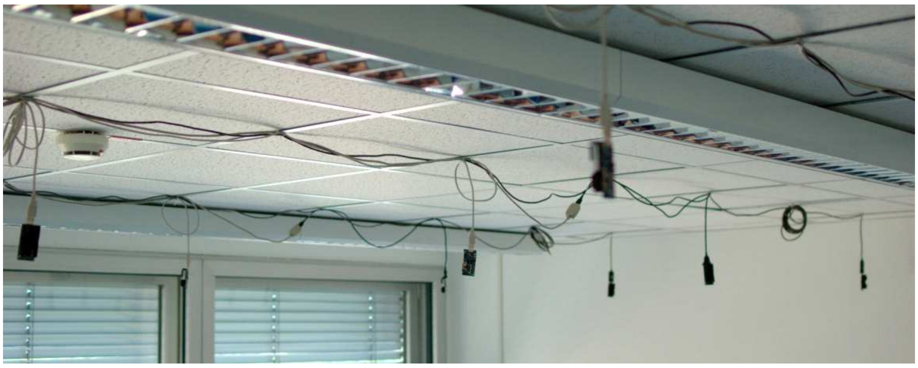


Figure 5.1: Stationary Sender Node

Figure 5.2: Receiver Node: Slow Movement (left) and Fast Movement (Right)

The nodes used in the setup are *Tomte Sky Nodes* and use the TI MSP430 microcontroller and an ultra low power, IEEE 802.15.4-compliant Chipcon CC2420 as the radio [1]. A *Tmote Sky Node* is shown in Figure 5.3.

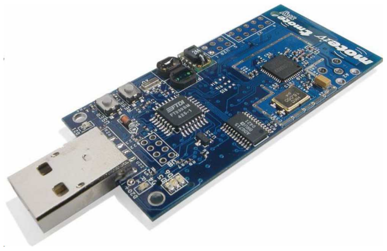


FIGURE 5.3: Tmote Sky Node [1]

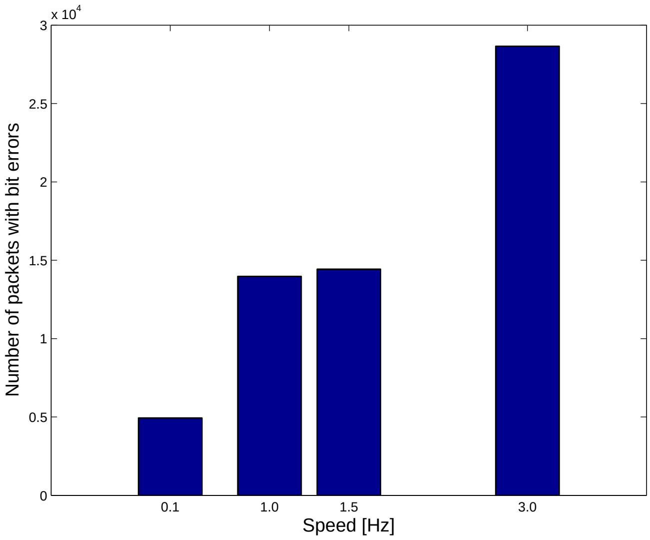
The sender continuously sends 100 bit packets to the receiver. The total number of packets sent are 100,000 for each speed. The payload consists of a known bit sequence which is analyzed at the receiver for transmission errors. We focus on analyzing the distribution of bursty errors in the sequence of packet transmission. Using this information, we attempt to estimate the chance of a future packet being erroneous if the current and preceding packet(s) are erroneous. Factors such as burst length are also taken into account.

To compare results from our empirical data, we simulate a similar experiment in MATLAB. We assume a channel with independently distributed packet errors. The packet errors are introduced with a probability P which is equal to the PER value calculated from our empirical data. This means that both sets of data will have the same number of packet errors, however, with a different distribution. This comparison will allow us to determine whether the channel behavior we see in our empirical data is a random pattern or actually a characteristic of the wireless channel resulting from node mobility.

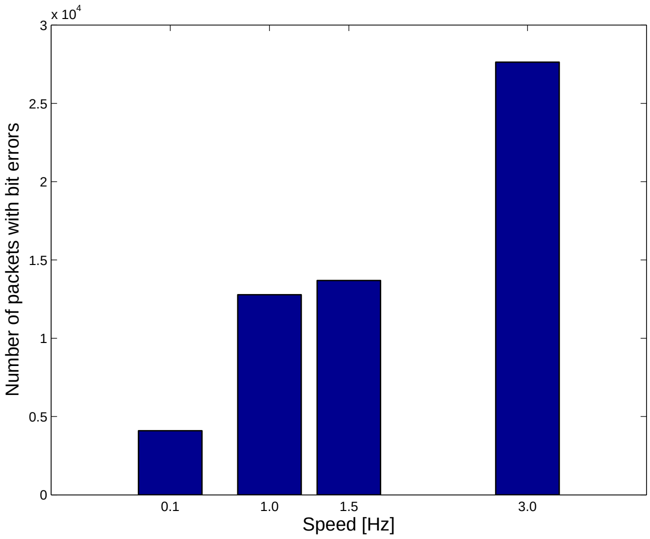
5.3 Results

First, we show the number of erroneous packets received at the destination, in Figure 5.4, for a total of 100,000 packets. Figure 5.4(a) and 5.4(b) show the packet error for empirical data and simulation data, respectively. Both the empirical and simulation data suffer from a similar number of packet errors which increases with increasing speed. With PER consistent across the empirical and simulation data, we now look at the distribution of packet errors inside the traces.

Figure 5.5 shows the percentage of bursty packet errors. We define bursty packet errors as instances where more than one successive packet was erroneous. Comparing Figure 5.5(a) with Figure 5.5(b), we see that the empirical data has almost three times as many bursty packet errors as the simulation data. This means that for our mobile



(a) Empirical Data



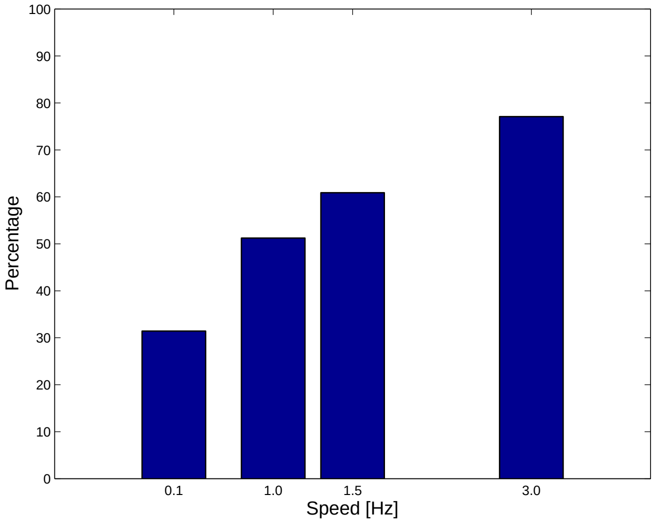
(b) Simulation Data

Figure 5.4: Total Erroneous Packets Received

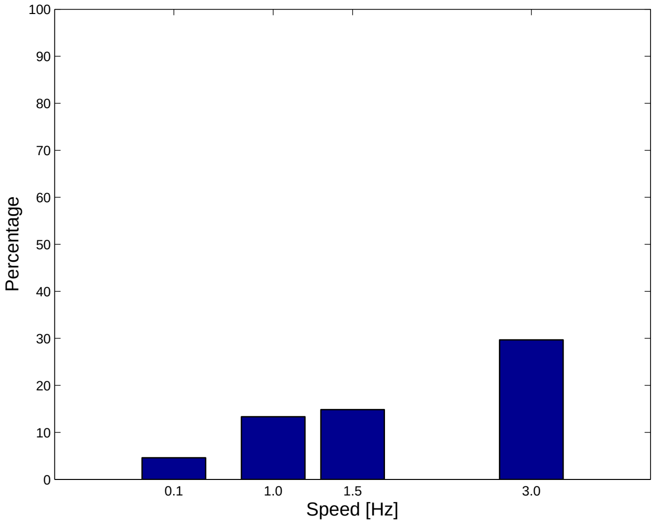
node, if a preamble packet was received with bit errors, there is a 30% chance that the following data packet would also be erroneous when the node is moving at a slow speed of 0.1Hz. This probability goes up to 78% as the speed increases to 3Hz.

Consecutive erroneous preambles could indicate a high probability that data packets could also be erroneous. This probability, as explained earlier, could be used to calculate a backoff timer or send this value to the source node, which could then leverage it for partner selection.

Another interpretation of the previous result is shown in Figure 5.6. Here, we divide the data-set into consecutive pairs of preamble-data. That means the transmission now



(a) Empirical Data

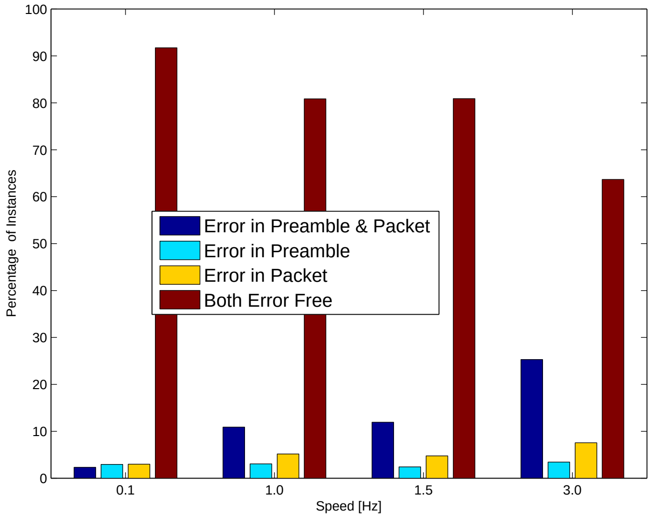


(b) Simulation Data

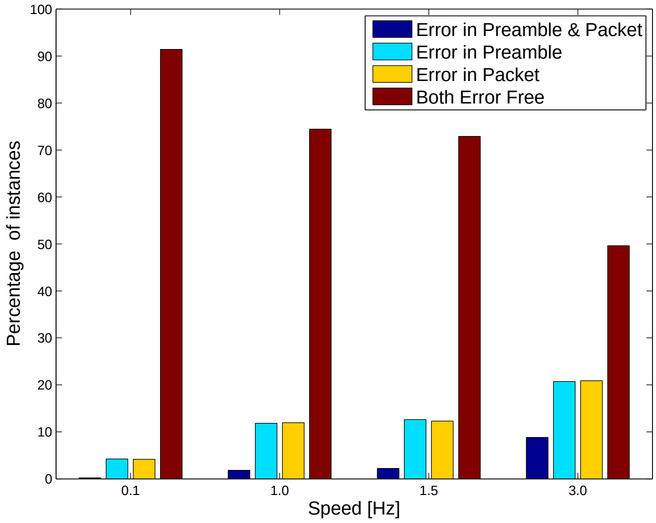
Figure 5.5: Percentage of Bursty Erroneous Packets

consists of repeating pairs of one preamble followed by one data packet. We plot the four possible cases where errors can occur in the preamble-data pair against speed in Figure 5.6(a) and 5.6(b).

We see that in empirical data the instances where both preamble and partner are erroneous increases significantly with increasing speed. The increase in individual errors in preamble or data shows a very small change. This means that in practical wireless environments, the channel suffers from bursty errors which in turn can depend upon speed. This does not hold true for simulation data where the errors are randomly spread out, and so a prediction for errors in data packets depending upon preamble errors might



(a) Empirical Data



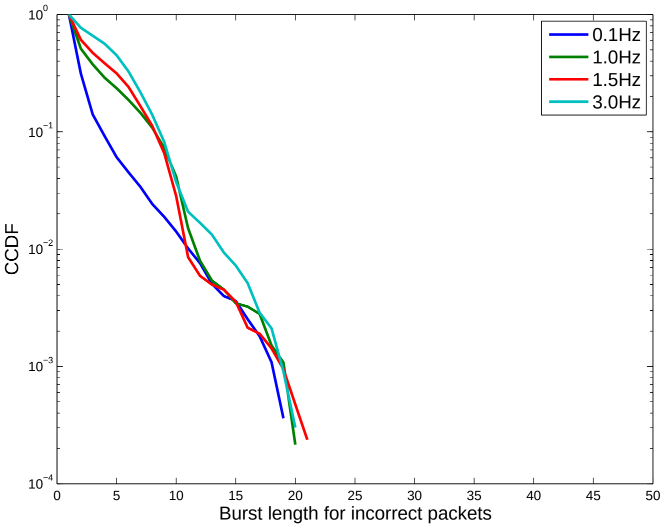
(b) Simulation Data

FIGURE 5.6: Preamble Sampling-Based Error Analysis

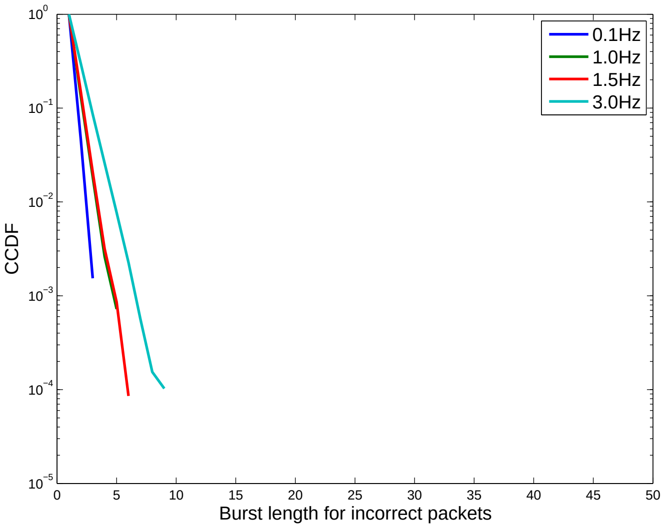
not be feasible.

In Figures 5.7 and 5.8, we plot the complementary CDF of the burst length for incorrectly received packets and run length for correctly received packets, respectively. Burst length and run length denotes a contiguous sequence of erroneously and correctly received packets, respectively. This result gives an overall view of the data and how the errors are scattered throughout the data set. We see in Figure 5.7 that the burst length for empirical data spans a larger range i.e., from 1 to 25 packets which is approximately twice as much as that of simulated data.

Similarly, the run length for correct packets is significantly larger as shown in Figure 5.8.



(a) Empirical Data

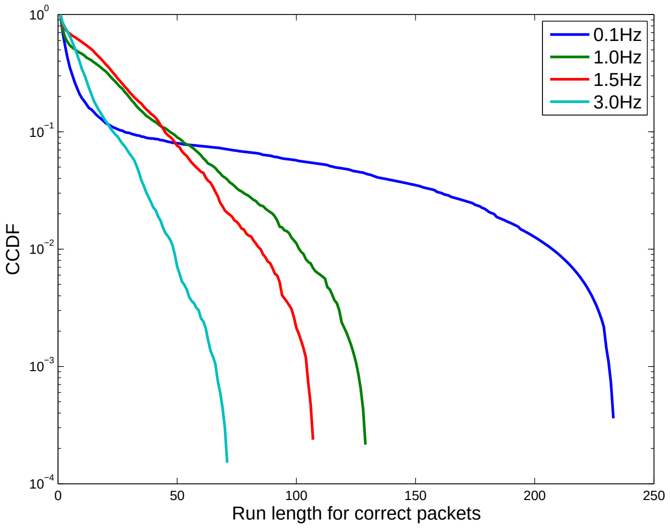


(b) Simulation Data

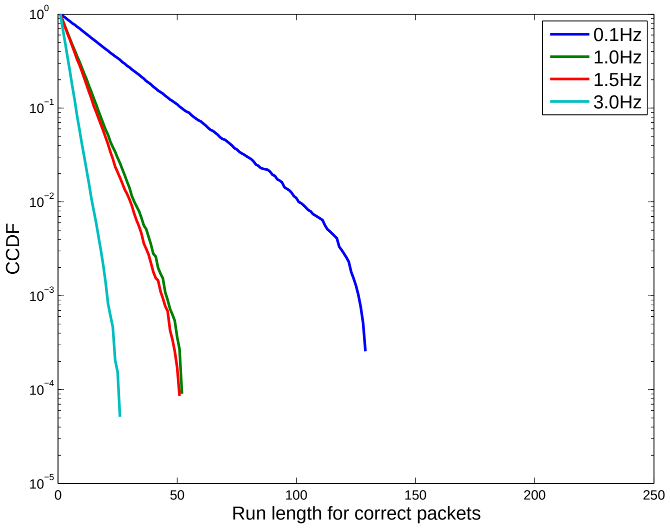
FIGURE 5.7: Complementary CDF: Length of Burst for Incorrectly Received Packets

The maximum run length is again almost twice as long for empirical data as compared to simulation data.

This shows that both the correct and erroneous transmission in a mobile wireless environment are closely packed together and burst and run lengths are significantly larger when compared to a channel that introduces uniformly distributed and uncorrelated errors.



(a) Empirical Data



(b) Simulation Data

FIGURE 5.8: Complementary CDF: Length of Run for Correctly Received Packets

5.4 Summary

We conclude from this discussion that in practical sensor network deployments in mobile environments, packet errors are grouped closely together. This characteristic can serve as a reasonable indicator for predicting error in a data packet in preamble sampling protocols, where one more preambles precede a data transmission. Preambles are a good candidate for this purpose because they consist of a pre-determined bit sequences, known to all nodes, and usually do not contain a payload. In a preamble sampling-based cooperative protocol, partner nodes can use this information for partner selection or convey this information to the source or the destination, where it could be used to make the selection. Receiving preambles erroneously does not mean that such nodes should be removed from the list of potential partners but instead a higher priority can be assigned to nodes which receive the preambles correctly.

Chapter 6

Simulating Cooperative Diversity Protocols

The development of cooperative diversity protocols has received significant attention from the research community during the last decade. Both cooperative physical and medium access control (MAC) schemes have been proposed with one survey estimating the number of proposed cooperative MAC protocols at more than 15 [10]. As researchers tend to focus their research on individual layers of the ISO/OSI model such as physical, link, or routing layer, it becomes challenging to evaluate cooperative protocols, which require multi-layer support. Furthermore, a lack of guidelines on simulating cooperative protocols along with the implementation complexity of simulations has limited their performance evaluation to either analytical results or simple three node scenarios comprising a single source, partner, and destination node.

This has motivated us to identify the cooperative functions needed for simulating or implementing cooperative protocols, based on our experience of implementing CPS-MAC and RCT-MAC in OMNet++. We discuss our simulation model and the lessons learned. The functions are categorized into appropriate layers of the communication protocol stack to ensure compatibility with the ISO/OSI model. We use MiXiM for OMNet++ as a reference model to elaborate the implementation details to the reader.

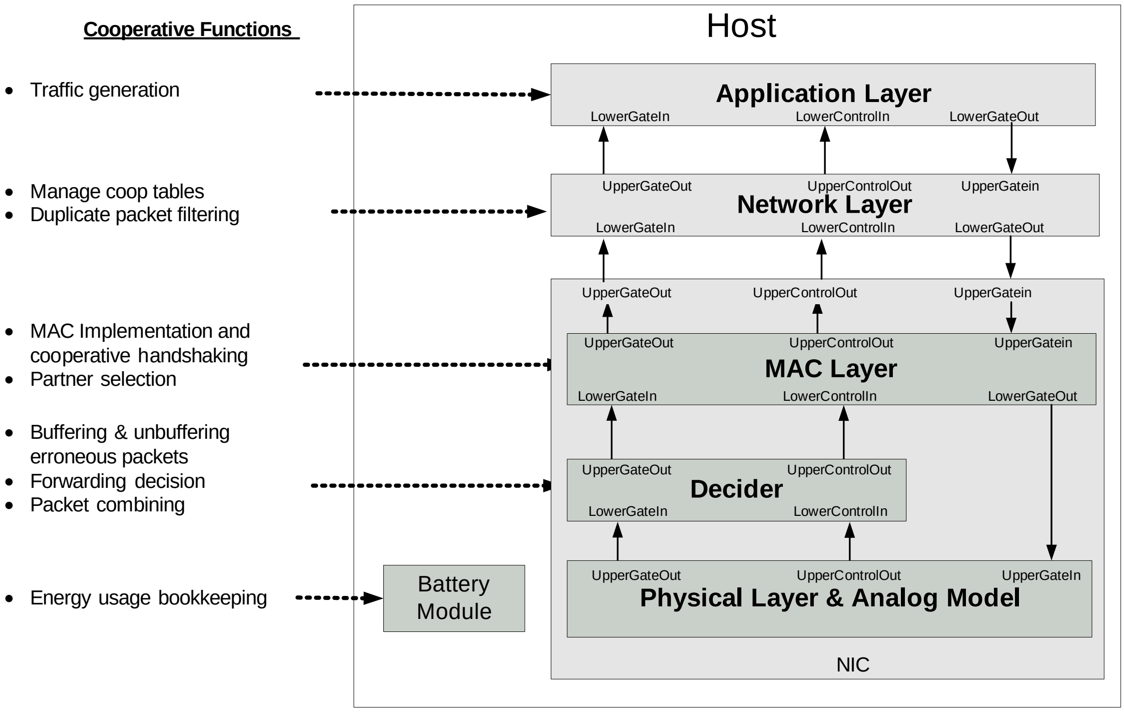


FIGURE 6.1: Module Hierarchy in MiXiM Framework for OMNet++

6.1 Implementation Details

6.1.1 MiXiM for OMNet++

The OMNeT++ discrete event simulator for network protocols has been publicly available since 1997 with version 4.4 being the current release [94, 105] at the time of this writing. It provides the base components from which further frameworks can be derived. For simulating wireless networks in OMNeT++, several frameworks have evolved such as INETMANET, Castalia, and Mobility Framework, which has now been merged into MIXIM [96]. These models follow their own development cycles, independent of OMNet++. Each of these frameworks comes with its own strengths and advantages.

MiXiM is an OMNeT++ modeling framework created for simulating mobile and fixed wireless networks, sensor networks, body area networks, ad hoc networks, vehicular networks, etc [96]. The core framework provides detailed models of radio wave propagation, interference estimation, radio transceiver power consumption and wireless MAC protocols (e.g. Zigbee) which can be used to create simulations. These models can be further extended (via inheritance) to incorporate additional functionality. MiXiM uses a layered protocol stack shown in Figure 6.1. *Physical Layer and Analog Model* models the sending and receiving of analog signals, collision detection, and bit errors. The *Analog*

Model specifically models the attenuation of a received signal by simulating shadowing, fading, and path loss. The *Decider* is used on the receiver side to determine whether a frame was correctly received or not. The *MAC Layer* is where the state machine for MAC, responsible for packet scheduling and switching the radio between sleep and awake state, is implemented. *Network layer* is responsible for storing and managing routing information. The *Application Layer* is responsible for generating packets for transmission. Additionally, MiXiM provides several mobility models, address resolution protocol (ARP) models, dynamic connection management, and several other components [96].

6.1.2 Enabling Cooperation in OMNet++

To enable cooperative diversity in OMNet++, the following additional functions were implemented.

1. Cooperative Handshaking
2. Forwarding Decision
3. Combining Decision
4. Partner Selection

Figure 6.1 shows the corresponding layers where these functions have been implemented.

6.1.2.1 Cooperative Handshaking

In RCT-MAC, we implemented a handshaking scheme where the source, partner, and destination use preambles and ACK packets to inform each other of their willingness to transmit / receive. The handshaking scheme implemented in CPS-MAC also used preambles, however, it did not include any acknowledgments. As shown in Figure 6.1, we implemented the handshaking in the *MAC layer* in the MiXiM hierarchy. The MAC design for CPS-MAC and RCT-MAC were also implemented at this layer. While overhearing is desirable in cooperative protocols, we observed that when multiple nodes are competing for the medium and a handshake takes longer to complete, as in the case of RCT-MAC and CPS-MAC, overhearing can interrupt an ongoing handshake. The significance of this effect will likely depend on protocol design and implementation. For this reason, we concluded that the design of a cooperative MAC protocol should include an effective overhearing strategy which minimizes the disruption of handshakes in a cooperative communication environment.

MAC layer implementations for IEEE 802.11 MAC layer are already available. These can further be extended for cooperation along with appropriate changes to frame formats. WSN MAC layers such as BMAC and Low-power-listening (LPL) have also been implemented.

6.1.2.2 Forwarding Decision

After a partner node has received a packet from the source, it must decide if and how it wants to forward the packet. A partner may choose to retransmit an amplified or a compressed version of the signal. A partner can also choose to discard a packet if received erroneously. Details on forwarding schemes can be found in references [16] and [17].

For RCT-MAC and CPS-MAC, the forwarding decision, based on decode and forward, was implemented at the *Decider*, as show in in Figure 6.1. At the *Decider*, the SNR value for a received packet is available which is compared against a pre-defined SNR threshold to determine if the packet is received correctly. The *Decider* passes the correctly received packets to the MAC layer. For the incorrectly received packets, the *Decider* takes a decision based on its role defined during handshake. At the destination, the *Decider* buffers incorrectly received packets for later combining. At the partner, the *Decider* discards these erroneous packets because, in our implementation, the partner would not expect to receive redundancy from any other node. This is meant to minimize unnecessary propagation of erroneous packets. A frame buffer has been implemented in the *Decider* to buffer erroneous packets. The *Decider* does a periodic buffer cleanup using self-timers to remove old entries.

6.1.2.3 Combining Decision

The destination is responsible for combining packets received from the source and the partner. This function is implemented in the *Decider*, where all the erroneous packets are buffered. To simulate packet combining, we have used *selection combining* and *maximal-ratio combining* (MRC) schemes, known from MIMO systems [4]. In selection combining, the strongest signal from the N received signals is selected. We simulate this by selecting the packet with the highest SNR. In MRC, SNR values of received signals are summed up. We simulate this by adding up the SNR of original and repeated packet and then comparing the sum to the threshold SNR value. Successfully combined packets are passed from the *Decider* to *MAC layer* where a node can either decide to forward them or pass them to a higher layer for processing, depending upon its role in cooperation.

6.1.2.4 Partner Selection

A partner selection scheme was presented in CPS-MAC in Section 3.2. The scheme uses CoopTable for storing neighborhood information, which is used for partner selection and addressing. In our implementation, the CoopTable was implemented at the *Network layer*, where the routing information is usually consolidated in a non-cooperative protocol. A filter to identify duplicate packets is also implemented at the *Network Layer*. This caters to situations where a packet may arrive at the destination after a delay or multiple partner nodes forward multiple copies to the destination. The *MAC Layer*, responsible for initiating cooperation at the source and scheduling transmissions, does the partner selection using the information stored in the CoopTable.

6.1.2.5 Other Functions

The *MAC layer* is also responsible for switching the radio between sleep, awake, and transmit states and uses the *Battery Module* to keep track of energy usage by the transceiver. This is used to evaluate the energy consumption of cooperative protocols for comparison with the conventional protocols. In order to subject the network to different kinds of traffic loads, the *Application Layer* was used to generate packets periodically, using a configurable inter-packet interval. This was used in performance evaluation of CPS-MAC and RCT-MAC in Sections 3.3.3 and 4.4, respectively.

6.2 Summary

In this chapter, we have identified the various functions which were implemented in OMNet++/MiXiM to enable cooperative communication. We have used the OMNet++/MiXiM layered model to indicate where each of these function has been implemented. This is meant to benefit the reader interested in simulating cooperative protocols. Factors such as packet overhearing and energy usage are also discussed. The source code for CPS-MAC and RCT-MAC can be obtained from here: wwwcs.upb.de/cs/ag-karl/people/rana-azeem-m-khan

Chapter 7

Conclusion

This thesis has investigated the integration of cooperative diversity into WSN protocols for improving reliability under energy constraints. Most previous work in the area of cooperative MAC protocols for WSN uses a modified version of IEEE 802.11 DCF mode for cooperative handshaking; however, this is not optimal due to the energy constraint in WSN. Many of these protocols also do not address the energy consumption tradeoff. Furthermore, we noticed a need for performance comparison of cooperative WSN protocols with traditional WSN protocols. Motivated by these limitations, the objective of this thesis was to propose a cooperative MAC protocol for WSN, evaluate its performance evaluation under energy constraints, analyze the effects on cooperation in a larger network, and evaluate its performance against non-cooperative WSN protocols. Two new cooperative MAC protocols for WSN, namely CPS-MAC and RCT-MAC, were proposed in the course of this work. We summarize the contribution of each protocol below, along with conclusions, according to their order of appearance in the thesis.

7.1 Cooperative Preamble Sampling MAC

CPS-MAC shows the possible benefits of using cooperative communication to increase the reliability and reduce energy consumption in WSN. It uses overhearing to its advantage and forms cooperative triangles in densely deployed WSNs where nodes can deliver redundancy to the destination by repeating each others transmissions and countering the effects of channel errors, collisions, and idle listening. CPS-MAC is developed using preamble sampling, which is a native WSN technique and used by non-cooperative WSN protocols such as X-MAC and BMAC. CPS-MAC was one of the first initiatives to use cooperative preamble forwarding in a handshaking phase to wake up nodes prior to transmission. This increases their probability of participating in cooperation. We focus our analysis on the cost of using cooperation in terms of energy consumption vs. reliability. Results showed that energy expenditure of CPS-MAC is comparable to the direct-MPS protocol and outperforms relaying-MPS. We scaled the protocol for simulation in a realistic multi-hop WSN and concluded that cooperative communication can help achieve comparable packet delivery rates at low traffic load but the maximum benefit is achieved when the network is operating under mild to very heavy traffic load.

7.2 Reliable Cooperative Transmission MAC

RCT-MAC presented in Chapter 4 was designed to overcome to limitations of CPS-MAC. RCT-MAC introduced *Cooperation on Demand*, which meant that nodes only cooperate when needed. This was accomplished by implementing implicit feedback during the handshaking phase from partner and destination to source. Furthermore, this was one of the first attempts to compare the performance of a cooperative WSN protocol with traditional WSN protocols such as BMAC, LMAC, and IEEE 802.15.4. We saw that LMAC performs very well under low traffic load; however, at high traffic load, the performance of LMAC suffers due to the design restriction of allocating one slot per node in a single frame. Contention-based protocols perform better at high traffic load as they do not have such a limitation. In such cases, RCT-MAC performs significantly better than IEEE 802.15.4 in terms of energy efficiency. This also verified our conclusion from CPS-MAC that cooperative communication is beneficial when the network has to handle mild to very heavy traffic load.

7.3 Packet Error Prediction using Preamble Sampling

Chapter 5 introduced a new technique for predicting packet errors in a preamble sampling-based protocol by evaluating the previously received preamble packets. This is particularly intended for cooperative scenarios where partner nodes have to decide on forwarding a packet among themselves. We conclude from discussion in this chapter that for practical sensor network deployments in mobile environments, packet errors are grouped close together. As preamble sampling protocols use preambles, which are pre-determined bit sequences known by source, partner, and destination, bit errors in preambles could indicate errors in data packets. This information serves as a reasonable indicator for predicting packet errors and can be used for partner selection, in combination with existing schemes.

7.4 Future Research

From our analysis in this thesis, we outline the following design considerations for researchers interested in the future development of cooperative MAC protocols.

- Integration of cooperation into standardized WSN protocols can foster acceptance of protocols, especially for industrial automation
- Energy efficiency vs. reliability tradeoff should be considered so the cost of using cooperation can be evaluated
- Cooperative signaling overhead should be minimized to reduce latency and energy consumption
- Using an optimal relay(s) selection scheme can help in achieving a better diversity gain for cooperation
- The protocols, if possible, should have low implementation complexity for WSN

Furthermore, we observe that incorporating cooperative diversity in standardized WSN protocols has received very little attention. Owing to industry interests in developing and using them for industrial automation purposes, enabling cooperation in these protocols can have significant commercial and industrial advantages. We believe this topic holds significant potential for the future development of cooperative protocols.

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