Chapter 1

MAC Protocol Design for Underwater Networks: Challenges and New Directions

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1.1. Introduction

In this chapter, we focus on acoustic underwater networks, which utilize acoustic communication links to communicate between the nodes. It is well-known that RF signals do not propagate well underwater, and the optical signals [1] are useful for short distances and under clear water propagation conditions. For long distances, the Navy has utilized acoustic communication. More recently, there has been a growing emphasis in the research community on underwater ad hoc and sensor networks [2]–[6], which utilize acoustic communication over relatively short distances of about 100 meters. The advantages of such short distance communication are numerous: First, the strong multipath profile [7] that exists in the traditional applications over much longer distances is significantly reduced, thereby increasing the data rate at which the communication can take place. Second, the propagation delays are reduced. This has important consequences for the design of MAC protocols because achieving a rough synchronization between the nodes becomes possible. Third, short distances save battery energy [8], which is especially important for underwater sensor networks. For example, in scientific data collection applications [9] in which the batteries are expected to last for months under difficult conditions, the battery energy becomes the most important constraint. In contrast with terrestrial communications, underwater acoustic communications is affected by both distance-dependent path loss, as well as frequency-dependent absorp-
On the dB scale, the path loss increases logarithmically with distance, whereas the frequency-dependent absorption increases linearly with distance. Hence, over long distances, the latter dominates, and leads to significant energy consumption. By operating sensor networks with internodal distances of about 100 meters, the frequency-dependent absorption term becomes only a small fraction of the path loss, hence, its deleterious effects on energy can be significantly reduced.

This chapter focuses on the design of MAC protocols for underwater sensor networks. The recent attention to this topic is motivated by several factors: First, in the marine science, limnology, and oceanography communities, there has been a growing need for underwater sensor networks. Currently, many of the underwater sensors in Long Term Ecological Research (LTER) projects [9] are stand-alone. The future vision for these projects is for the sensors to be networked with each other such that (1) adaptive sampling becomes possible when sensors in a region detect an interesting event so that more samples can be taken on demand, (2) in-network data aggregation and fusion become possible, and (3) the collected data can be sent to the laboratory in a timely fashion to lead to quick analysis. There is a great thrust [11] toward the collection and visualization of real-time data in these scientific communities, such that the lakes and oceans can be observed on a continuous basis. The design of MAC protocols for these underwater sensor networks will enable effective data collection, aggregation and networking to the sites where the data can be displayed and interpreted.

Second, MAC protocols for underwater networks are important for the Navy. Much of the research in the last 30 years on underwater networks has focused not on networking, but rather on point-to-point communications. Indeed, very sophisticated, successful methods [12],[13],[14] have been designed for the physical layer, with superior performance. The underwater acoustic physical channel is one of the severest out of all of the channels found in nature: The Doppler and multipath profiles, as well as the strong distance-dependent loss leaves very little effective bandwidth over which to communicate. Hence, well-designed equalizers [15] have been the key to achieving the capacity of these channels. In contrast with the physical layer developments, however, the MAC protocols used for the Navy applications have largely been based on the CSMA/CA prototype. The RTS/CTS exchange is in fact not very well suited to underwater communication due to the propagation delay [16]. Hence, both the hidden and exposed terminal problems are exacerbated. One of the reasons that it has been difficult to
assess MAC protocols for underwater networks is the lack of a measuring stick that is comparable to Shannon capacity. For the physical layer, the researchers are able to assess the gap from Shannon capacity, whereas no similar MAC protocol capacity measures have been developed for underwater networks. For terrestrial networks, the g-put is a measure of the channel utilization; however, when long propagation delays are involved, as in underwater acoustic networks, it is no longer possible to attribute a single utilization measure to the channel itself. Instead, a utilization measure must be attributed to each individual node’s receiver. Hence, a part of the research on MAC protocol design for underwater networks today focuses on defining appropriate capacity measures for underwater MAC protocols. A second part of the effort focuses on the development of protocols [17]–[24].

The rest of this chapter is organized as follows: Each of the main sections of this chapter is devoted to a research challenge, and outlines new directions to address the research challenge. In Sections 1.2, 1.3, and 1.4, the research challenges are the propagation delay of the acoustic medium, energy consumption, and mobility, respectively. Finally, in Section 1.5, we present our conclusions.

1.2. Challenge I: Propagation Delay

Large and location dependent delays in underwater networks degrades the performance of traditional medium access protocols [5],[25]. Therefore, the estimation of propagation delay can be employed to improve the performance of MAC protocols for such networks [26],[27] or to achieve synchronization between the nodes. The challenge that long propagation delays pose for the design of MAC protocols can be addressed in a couple of ways: First, the propagation delay can be estimated by a handshake between the nodes, as shown in Figure 1.1. Node A, who wants to estimate the propagation delay to its neighbor Node B, sends a beacon signal and records when the beacon signal was sent out. When Node B receives the beacon signal, it immediately returns an ACK to Node A, which then records when the ACK was received. Assuming that the propagation delay is symmetric between A and B, Node A divides by two, the difference between the time that the beacon was sent, and the time that the ACK was received, to obtain an estimate of the propagation delay. A three-way handshake can be performed to allow the estimation of the propagation delay by Node B, as well. When Node A receives the ACK, it returns an ACK to Node B right away. Based on when its own ACK was sent out and the ACK from Node
A was received, Node B itself can also estimate the propagation delay by a similar procedure. These calculations assume that the processing delay at any receiving node is small, compared to the propagation delay, which is almost always satisfied since the processors use silicon technology that operate at speeds much larger than those in the acoustic medium.

There are variations on this simple propagation delay estimation scheme, that are also possible. For example, as shown in Figure 1.2, when Node B receives the beacon signal from Node A, it may choose to record the time it was received, record the time until its own ACK is sent out, and place a time stamp in its own ACK that indicates the time that passed from the time it received A’s beacon signal, to the time that it sent out the ACK. This may be useful, for example, if Node B is not able to send back an ACK right away because it is busy communicating to another node, say Node C. When Node A receives the ACK from Node B, under this estimation scheme, it first decodes the stamp in the ACK signal, subtracts this delay that was incurred at Node B, before it divides by two in order to obtain an estimate of the propagation delay. Both of the references [20] and [28] utilize this method as part of the MAC protocol design.

The second way to address the challenge of propagation delay in underwater acoustic networks is to use relative time stamps in the beacon
Fig. 1.2. Propagation delay estimation sending delayed ACK frames

signals, and not estimate the propagation delay at all. In this method, which is shown in Figure 1.3 each node sends out a beacon signal, advertising to its neighbors exactly when it will send again, as a time difference from the current transmission, according to its own clock. Let \( T_0 \) be the time on this time stamp. Hence, Node A states in its beacon signal that it will send again \( T_0 \) seconds later. When a neighbor, say Node B, receives this announcement a random and unknown propagation delay later, it sets its clock so that it will be ready to receive the transmission from Node A, \( T_0 \) seconds later, according to Node B’s clock. If the propagation delay does not change significantly and if the clock drift is not significant within \( T_0 \) seconds, then Node B indeed receives the next transmission from Node A exactly when it expects it. Note that the propagation delay need not be estimated at all. Hence, the nodes achieve pseudo-synchronization without any estimation of the propagation delay.

The specialization of this method to periodic announcements appeared in the literature in [8] in the context of topology control for energy-limited, terrestrial networks, and in [29], in the context of MAC protocols for terrestrial, energy-limited networks. For underwater networks, this was utilized in the UWAN-MAC protocol [17],[18]. However, note that the announcement need not be periodic. In fact, at any slot where a new announcement to the neighbors is made, a new time \( T_0 \) can be specified. In UWAN-MAC,
this is covered under the context of changing the period of the transmissions; however, no periodicity of successive transmissions is necessary.

There are both advantages and disadvantages of the first and second methods described above. By virtue of the first method, in which the propagation delay is estimated directly by a three-way handshake, the knowledge of the propagation delay allows the nodes later in the DATA transmission phase to set timers for the ACK messages. If an ACK for a DATA packet has not been received after a time-out plus twice the propagation delay, then a retransmission becomes possible at the data link layer. Hence, the estimation of the propagation delay allows the protocols to wait an extra duration of twice the propagation delay and effectively turns the internodal channel into one that does not involve propagation delays. However, an inefficiency due to the extra wait time of propagation delay is incurred as a result. In a medium that is shared by all the nodes in a network, even a TDMA-based scheme that allocates slots to different nodes using a guard time that is at least as large as the propagation delay, can be set up, after the propagation delay has been estimated. Hence, “slotted protocols”, as a general class, as described in [26] and [30] become possible; however, although such MAC protocols that aim to turn the underwater channel into an RF-like channel, with an efficiency cost incurred due to these guard times, are useful for the short distances we consider, they cannot achieve
the fundamental limits of MAC utilization at each receiver. In order to understand this, consider the example of 2 nodes that share the same medium, and which need to send information to each other on a periodic basis. In the 2-node case, no explicit estimation of the propagation delay is required, and the nodes can send the DATA to each other in a handshaking fashion. Figure 1.4 illustrates such a traditional scheme.

![Fig. 1.4. Traditional stop and wait transmission protocol](image1.png)

The utilization on each node’s axis is $\frac{t_{\text{DATA}}}{t_{\text{DATA}} + t_p}$, where $t_{\text{DATA}}$ is the DATA duration, and $t_p$ is the propagation delay. Hence, only in the limit
as $t_{DATA}$ goes to infinity, can the utilization approach 100% (not taking into account any data link layer errors, here, and counting only MAC utilization). Now, if the value of the propagation delay is known, then the transmission shown in Figure 1.5 becomes possible, where each node transmits data only for a duration of $t_p$, and then receives data for the next duration of $t_p$. We call this transmission “butterfly transmission”.

Butterfly transmission has 100% utilization on each of the node’s axis. It is fair, in the sense that it allows each node to transmit 50% of the time, and receive 50% of the time; hence, both nodes can send their data in a timely fashion. This procedure requires perfect synchronization between the nodes so that they know that they can start the butterfly transmission at the same time, on a global axis. This cannot be achieved with 100% accuracy in all circumstances; however, the following describes a case where it can: Assume that one of the nodes is designated a priori, as a “leader”, and the other one always as a “follower”. The follower never initiates protocol control information exchanges itself, and a leader always does. This designation is hardwired into these two nodes upon deployment. Then, as shown in Figure 1.6, the leader, Node A, initiates a three-way handshake for the estimation of propagation delay. Then, the leader starts its DATA transmission, in packets of duration $t_p$, exactly $t_p$ seconds after its last transmission in the three-way handshake. The follower, Node B, also estimates $t_p$ by the end of the three-way handshake, and immediately starts transmitting its own data, in packets of duration $t_p$, right after the end of the three-way handshake. The processing delays are very small compared with propagation delays, and are hence ignored in the figure. Hence, the nodes can settle into the butterfly transmission with 100% utilization after this three-way handshake.

The leader in the above set-up was hardwired into the nodes. The leader election problem, without such a hardwiring, is not trivial, even in the 2-node case. The main complication arises from the fact that without a predetermined leader, the nodes can send at any time to try to establish the leader; however, the possibility of collisions with a positive probability, always leaves some chance that synchronization is not achieved. Hence, an interesting area of research is understanding how such leader election problems, which are fundamental in computer science, can be addressed in media with variable propagation delay, as in underwater networks. Many of the algorithms for leader election in the literature aim to minimize the message overhead on a topology, however, assume that the links can exchange information without collisions.
The butterfly scheme, which we developed for the 2-node case, cannot be generalized to the 3-node case, that is, when 3 nodes share the same MAC medium, with variable propagation delays. In fact, for the 3-node case, there are always scenarios where 100% utilization on every node’s time axis is not possible. In the literature, [31] sheds considerable light on the optimal MAC scheduling problem (albeit with minimum energy as the main objective). An important contribution of that paper is the formulation of the scheduling and routing problem with variable propagation delays. This is formulated as an optimization program, and optimal MAC schedules can be generated for any placement of the nodes. The paper goes further and derives the optimal placement of the nodes to achieve the minimum energy solution under interference constraints. Hence, the results of that paper give a general scheduling and routing framework to achieve the lowest energy consumption possible in an underwater network with variable propagation delays. However, the downside is that the solution is a scheduling solution; that is, it is a centralized solution that assumes that all of the propagation delays are known a priori (or have been estimated), and a centralized scheduler tells the nodes, on side information channels, exactly when to start and end their transmissions. In reality, such side information channels are difficult to establish, especially in the presence of propagation delays. In a framework of MAC protocol capacity, what is needed is an achievable upper bound that can show what the maximum utilization can be at each node’s time axis, given that the propagation delay information is...
not a priori available, and taking into account the overhead that would be incurred by having to transmit that control information. The difficulty of such a formulation is not particular to underwater networks, and is an unsolved problem in both communications and networking. Currently, there are two traditional approaches: A global scheduler is assumed to derive the capacity of a globally scheduled solution, and then ad hoc methods are utilized to distribute the required side information on control channels. This is invariably the approach of the communications community. On the networking side, notions of protocol optimality under side information assumptions are largely missing; hence, protocols in general are designed in an ad hoc fashion, and the goodness of a protocol is understood only in comparison with other competing proposals, and their relative performance evaluation in rather specialized circumstances. What is actually needed is a general framework that can define precisely protocol optimality, and also describe methods of how to derive or generate such optimal protocols. These would need to go beyond scheduling solutions that do not make the overhead of the control information as part of the capacity formulation.

1.3. Challenge II: Energy Consumption

A second challenge that the design of underwater sensor networks has to face is energy. The limited battery energy of the devices makes it paramount to design solutions that will allow the nodes to operate for months without having to recharge or replace their batteries [5],[32]. The challenges here are not entirely different from those present in the design of terrestrial sensor networks. The most common solution, from the perspective of MAC layer design, is the use of sleep schedules, as originally proposed in S-MAC [29]. For underwater networks, UWAN-MAC [18] certainly adopts this solution; however, with the recognition that the propagation delays are large and unknown, it opts for a solution that uses randomly selected transmit times. Unlike S-MAC, no attempt is made to endeavor to make the schedules of clusters to converge to some global schedule, which cannot be attained with variable propagation delays. In addition, RTS/CTS exchanges are completely avoided in UWAN-MAC, in order not to incur any energy overhead. Indeed, the figures of merit in this context are (1) total energy consumed, (2) fraction of transmit energy consumed due to collisions, and (3) fraction of receive energy consumed due to collisions. These metrics are entirely different from those used to evaluate ALOHA,
MACA, and MACAW, namely the traditional protocols which assume that bandwidth is the limiting resource rather than energy. When the amount of data that is collected from the sensors is small, then the protocols must become cognizant of this fact; hence, protocol overhead can no longer be made to go to zero in percentage, by making the DATA durations very large, since large amounts of data are simply not available. It is clearly seen that protocol design has to entirely be different in regimes where data generation rates are high, and where they are low. Currently, there is no “protocol engine” that is able to generate protocols on demand, based on which regime is in question. Even an understanding of which protocols are optimal in which regimes is largely missing. If formulated, those would be important contributions to making significant progress in the design of MAC protocols for underwater networks.

The need for protocol generation, or at least configurability, is also clearly seen when the modem specs for acoustic modems are considered. In [33], modem specs for an air modem and an acoustic modem are presented, and are seen to be widely different in terms of sleep, idle, receive, and transmit power consumptions. Even within the domain of acoustic modems, there is wide variability. Protocols, by their nature, are designed with certain assumptions in mind on modem specifications. For example, UWAN-MAC explicitly assumes that the power consumption in the sleep mode is much lower than that in the idle mode. Hence, there is an incentive to turn off the node as much as possible, just as is assumed in S-MAC. However, if the sleep and idle power consumptions are comparable for a particular modem that is chosen, then UWAN-MAC protocol becomes far from optimal. A good protocol for such a modem choice would eliminate the sleep schedules, would keep the node on, in order to minimize the delay. Hence, ideally, what is needed is the generation of a protocol on-demand, based on a variety of variables including the modem specifications, as well as the application requirements (e.g. QoS constraints on delay, energy, and bandwidth). The software-defined radios cannot address this challenge: Even though they provide configurability of parameters at the software level, there is no methodology to drive the protocols toward solutions that are optimal for particular modem specs, and application constraints. In terms of the available optimization engines, we now know very well how to do numerical optimization; that is, setting of the optimal values of particular, pre-determined parameters, but not protocol optimization, where we can embed structurally different protocols in a protocol space and efficiently iterate over those to find the optimal protocol. New mathematical meth-
ods are necessary to address this challenge, and their impact on networking research would be profound.

Energy, as a valuable resource, has led researchers recently to look at network capacity in a fundamentally different way. As early as the 1980’s, the bits-per-Joule capacity of a point-to-point underwater link [34] was defined and evaluated. More recently, for terrestrial networks, the bits-per-Joule capacity of an energy-limited wireless network [35],[36] was defined as the maximum number of bits that can be transferred reliably between sources and destinations divided by the total number of Joules of energy deployed into the network. Here, reliability is different from Shannon reliability and presumes only that a fixed, but arbitrarily small probability of error $\epsilon$ is achieved end-to-end, for each transfer. The bits-per-Joule capacity is a suitable measure of capacity for networks with energy-limited devices which aim to transfer delay-insensitive traffic to their destinations. In the context of scientific data collection, this is often the case, as the delay constraint required for the bits to reach their destination is on the order of minutes rather than milliseconds, as would be for real-time applications. The bits-per-Joule capacity concept is equally applicable to underwater sensor networks which are made up of small, energy-limited sensor nodes that aim to transfer delay-insensitive data to a collection site. The main difference is in the channel model where, in addition to path loss, a frequency-dependent absorption term is present. However, the scaling law for the bits-per-Joule capacity of an underwater network is similar to the one for a terrestrial one, since the frequency-dependent absorption term $a(f)^{-d}$ goes to 1 as the internodal distance $d$ goes to 0. Here, $a(f)$ is the absorption coefficient as a function of carrier frequency. The design of MAC protocols for energy-limited, underwater networks can focus on the maximization of the bits-per-Joule performance of these networks, rather than throughput, as would be the case in traditional, bandwidth-limited application domains. Again, in terms of the protocol generation problem, it is possible to pose questions such as: What is the MAC protocol that maximizes the bits-per-Joule performance? The development of mathematical tools that will allow the formulation and solution of such a protocol design optimization problem would indeed further the research on MAC protocol design for underwater networks.
1.4. Challenge III: Mobility

Many underwater sensor networks are made up of only stationary nodes; however, increasingly, mobility is becoming an important aspect of the design of MAC protocols for the underwater medium [5],[6]. As early as in Sea Web in the period 1998 through 2000 [37], autonomous underwater vehicles (AUVs) have been an important part of the underwater network landscape. The MAC layer of Sea Web was based on the traditional CSMA/CA solution, and many of the proposed protocols [38],[39] for underwater networks since then have been based on CSMA/CA. However, mobility itself introduces new challenges and a call for new models in the design of MAC protocols. We illustrate this with a few examples: First, consider the example of two nodes in Figure 1.7. In this figure, Node A is stationary, and Node B is moving away from Node A, at a constant velocity $v_B$. Figure 1.8 shows what the butterfly transmission solution for Figure 1.7 would look like in this case.

Because the propagation delay $t_p$ is getting larger, the intervals of duration $t_p$ on the diagram are getting larger as well. The 100% utilization of
both of the time axes of the nodes is maintained, as well as the fairness that
gives equal opportunities to both nodes to transmit and to receive. The
shown solution is possible if and only if (1) one of the nodes is a designated
leader in initiating the transmission, to be able to set up this transmis-
sion in the first place, and (2) the propagation delay, as it changes, can
be perfectly estimated. For example, if Node B’s velocity is known, this
can be used to determine how the duration of each transmit interval on the
diagram should be increased upon successive transmissions.

This brings us to one of the important general lessons in the choice of
whether the propagation delay should be estimated or not. In analogy with
the coherence time of an impulse response at the physical layer, we can de-
fine the “coherence time of propagation delay” at the network layer. For
transmission between two completely stationary nodes (i.e. such that even
platform motion around a fixed position is not possible), the coherence time
of the propagation delay is infinite. In this case, the propagation delay can
be estimated once and for all, and 100% utilization on each of the nodes’
time axes can ensue. However, if the coherence time of the propagation de-
lay is bounded, then the estimation of the propagation delay makes sense
only if the coherence time is much larger than the time required to estimate
the propagation delay. This bears an analogy to the physical layer theorem
that if the coherence time of the impulse response is much larger than the
symbol duration, then the physical layer channel can be estimated. How-
ever, the difference in the resolution required between the estimation of
the channel tap coefficients at the physical layer, and the estimation of the
propagation delay at the MAC layer via a handshake should be carefully
noted. The physical layer estimation must happen much faster, and the
resolution required is at the level of precision of the impulse response co-
efficients. From the perspective of the MAC layer, the underlying physical
layer coefficients can change. As long as this does not have an appreciable
effect on the propagation delay experienced, the coherence time required for
propagation delay estimation at the MAC layer can be much larger, than
the coherence time of the impulse response of the physical layer channel.
For example, consider the case of two nodes whose positions randomly move
about their centers (also known as platform motion, referring to the ran-
don motion of the platform on which the node is located, e.g. due to water
currents). Then, the propagation delay, averaged over these small spatial
movements around a central position, remains the same, whereas the im-
pulse response coefficients at the physical layer can change dramatically.
Hence, the coherence time required at the MAC layer is much larger.
An open question is the derivation of the MAC protocol capacity, for a set of $N$ nodes, each of which may be mobile or stationary. Here, by MAC protocol capacity, we mean the maximum utilization possible at each of the nodes’ time axes. This will necessarily be defined as a region of possible utilizations in an $N$-dimensional space, rather than a single number that we can call capacity. The example in Figure 1.9 illustrates some of the difficulties in designing MAC protocols that truly exploit the mobility of some of the nodes. In this figure, Node B and Node C are stationary nodes, and Node A is an AUV that moves between B and C. In this case, if Node A has something important to broadcast to both B and C, how can it interrupt an ongoing transmission between B and C, and broadcast its data in the little time that it has in passing between the two nodes? Several different strategies might be possible: (1) Stationary nodes may always leave certain slots in their transmissions empty, for possible usage by passing mobile nodes. (2) A separate frequency can be allocated as a control channel, on which a newcomer passerby can advertise its presence. When this beacon is heard, the stationary nodes immediately pause their transmissions to listen to what the passerby has to broadcast. (3) A CDMA-based solution is pursued in which certain codes are allocated as channels for possible passersby [40],[41]. When those channels are utilized, the ongoing transmission between B and C, which uses pseudonoise sequences is degraded softly, while the new transmission from the passerby can be detected and decoded on the parallel channel. All of this discussion shows that MAC protocols should take mobility directly into account, and utilize mobility in order to achieve the highest utilization at each node. The estimation of the propagation delays for a large set of nodes may become prohibitive, especially when a large number of mobile nodes are involved. Hence, a more aggregate view [42] of such networks, and the characterization of the propagation delay as a function over space rather than between
node pairs may become more useful when very large-scale mobile networks are in question.

1.5. Conclusions

In summary, the following would benefit greatly the design of MAC protocols for acoustic underwater networks:

1. A definition of MAC protocol capacity, that is cognizant of the propagation delays of the underwater acoustic medium: In contrast with RF communication, no single utilization metric can be ascribed to the channel itself. Instead, utilization must be measured along each node’s own time axis. The MAC protocol capacity can be defined as the set of Pareto-optimal points of a $N$-dimensional set of feasible utilization rates of each of the $N$ nodes. Such a definition would provide a method to compare the performance of different protocols, and to measure how far from the nearest Pareto-optimal solution each protocol is.

2. A methodology for the generation of MAC protocols on demand. Such a protocol generator would generate the optimal protocol, given (A) the physical layer resource parameters, such as the transmit, receive, idle, and sleep power specifications of the modem used, (B) the channel model, and (C) the application-layer requirements, such as the required QoS. The design of such a protocol generator is far from trivial; however, its impact on both underwater networking, and networking at large, would be profound.

3. A definition of “protocol optimality”. For example, when does it make sense to estimate the propagation delay? A MAC protocol that estimates the propagation delay on a periodic basis, and uses this for scheduling decisions can be said to be a “coherent MAC protocol”, in analogy with coherent physical layer communication. A MAC protocol that does without the estimation of propagation delays can be said to be “non-coherent”. If we divide the class of MAC protocols into coherent and non-coherent ones, how do we determine an optimal protocol within each class? Finally, how do we determine the optimal MAC protocol overall, that also involves the choice of whether or not to estimate the propagation delay, based on the cost incurred? Hence, the problem of the determination of an optimal protocol, can be decomposed into a choice between several subproblems, each of which makes different assumptions of the side information available (e.g. coherent
vs. non-coherent). Once an optimal protocol within each class is determined, these protocols can then be compared by examining the extra cost incurred in providing the side information that each class requires, and finally comparing the performance of each protocol, now with this overall total cost in mind.

(4) The incorporation of mobility models into the design of MAC protocols. In this chapter, we have already discussed the coherence time of propagation delay, as a novel MAC-layer concept, and both the impact and exploitation of mobility for MAC protocol design. Both link-level and aggregate network-layer coherence time concepts can be defined for underwater networks, with the goal of determining optimal MAC protocols for large-scale networks that involve both mobile and stationary nodes.

References

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