Interference Management for Medium Access Control in CDMA Underwater Acoustic Sensor Networks

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***Abstract*—One of the major challenges for the deployment of underwater acoustic sensor networks (UASN) is the design of a suitable medium access control (MAC) protocol, and CDMA has been earmarked as the most promising candidate. While several works have considered the problems of allocation of code and transmission power separately, in this paper, we propose a receiver-centric interference management approach for joint code/power assignment for MAC in CDMA UASNs. Through extensive numerical simulations, we illustrate its efficacy and demonstrate its superiority to conventional transmitter-centric approaches, for both fixed-power code assignments and joint code/power assignments.**

I. INTRODUCTION

Underwater Acoustic Sensor Networks (UASNs) can be used for collaborative applications such as environmental monitoring, early warning systems for disaster prevention, tactical surveillance and assisted navigation [1], to name a few. Acoustic communication is a promising candidate for UASNs since radio waves suffer from high attenuation and optical waves are affected by scattering. A major challenge for the deployment of UASNs is the development of a medium access control (MAC) protocol suited for the underwater environment [1], [2]. Although intensive research on MAC protocols has been conducted for wireless terrestrial sensor networks [3], they have to be adapted for UASNs due to limited bandwidth, high and variable propagation delays, high bit error rates and asymmetric links in harsh underwater environments.

MAC schemes are usually categorized under (i) contention-based and (ii) scheduled schemes. Contention-based schemes e.g. [4] combine carrier sensing with a three-way handshake to establish connectivity between source-destination pairs. However, the handshaking mechanism may lead to low system throughput due to high propagation delay, and the carrier sensing scheme may sense the channel idle while a transmission is still taking place, leading to packet collisions. On the other hand, amongst scheduled schemes, FDMA is unsuitable due to the limited bandwidth and frequency selectivity of the underwater channel. Due to long and variable propagation delays, long time guards must be used in TDMA, leading to channel under-utilisation.

With CDMA, each potentially-interfering user is assigned and transmits on a different spreading code and as such, users can transmit packets simultaneously, effectively solving the aforementioned MAC problems related to high propagation delay. In addition, resilience to frequency-selective fading and multi-path and graceful signal degradation [5] render it the most promising candidate for MAC in UASNs [1], [2].

The main challenges in CDMA-based MAC are (a) *code assignment* and (b) *transmit power control*. While it is theoretically possible to assign a unique code to each user, a code assignment algorithm is required to distribute a limited set of orthogonal codewords to the network users to avoid collisions from transmissions using the same code (*primary collisions*). However, unlike FDMA and TDMA channels which can be completely orthogonal, nonzero cross-correlation amongst CDMA codes implies that *every* user induces multi-access interference (MAI). This exemplifies the *near-far* problem in CDMA networks: assuming equal transmission powers, for a receiver much closer to an interfering transmitter than its desired transmitter, the interfering signal power will be much larger than the desired signal power, causing incorrect decoding of the latter (*secondary collisions*) due to unacceptably low Signal-to-Interference Noise Ratio (SINR). This problem can be overcome by transmit power control.

While code assignment [6], [7] and the near-far problem [5] have usually been tackled separately, recently, in [8], a transmitter-based CDMA scheme that incorporates a novel closed-loop distributed algorithm to set the optimal transmit power and code length is proposed for UASNs. The objectives are to achieve high network throughput, low channel access delay and low energy consumption. While diversity in terms of code length was considered in [8], we consider diversity in terms of code sequences and apply interference management techniques to solve the *joint code-assignment and power control* problem for MAC in CDMA UASNs. The approach we adopt is based on the constraint-based techniques developed in [9], and is strongly motivated by previous applications of these techniques for dynamic spectrum management in terrestrial radio networks [10], [11], [12].

This paper is organized as follows: In Section II, we explain the concept of constraint-based approaches to interference management and their application in wireless networks. Next, we describe the formulation and solution of interference constraints for joint code/power assignment in CDMA UASNs in Section III. We describe the simulation procedure and present some simulation results to demonstrate the efficacy of our proposed receiver-centric approach over the traditional transmitter-centric approach in Section IV. Finally, we present some concluding remarks and outline possible future research directions in Section V.

II. CONSTRAINT-BASED INTERFERENCE MANAGEMENT IN WIRELESS NETWORKS

Constraint-based approaches to interference management have been applied to optimize spectrum (frequency) assignment in wireless networks e.g., [10]. Based on each user's transmission power as well as the topology of the network, *interference constraints* are constructed and used to determine the spectrum assignment to each user such that interference remains within acceptable levels to maintain admissible communication quality.

A. Transmitter-centric Constraints

Interference is typically and traditionally regulated in a *transmitter-centric* way [13], which means interference can be controlled at the transmitter through the transmitted power, the out-of-band emissions and location of individual transmitters. Let $d_s(t_i,c)$ denote the *detection* range (for a receiver) of transmitter t_i in channel c. Accordingly, if $\mathit{Dist}(t_i,\ t_j)$ is the distance between t_i and t_j, they can share (or re-use) channel c only if the following condition holds:

$$\mathit{Dist}(t_i,t_j) > d_s(t_i,c) + d_s(t_j,c). \tag{1}$$

The above constraint eliminates the possibility of potential interference to receiver r_i (r_j) from t_j (t_i). To illustrate, let us consider a network with 3 transmitting users (nodes), $\{t_1,\ t_2,\ t_3\}$ sharing 3 channels, $\{A,\ B,\ C\}$ as shown in Fig. 1(a), where the detection range of each transmitter is given by the radius of the dotted circle around it. According to Eq. (1), transmitters t_2 and t_1 cannot use channel C simultaneously while t_1 and t_3 can.

By mapping each channel into a colour, the transmitter-centric interference constraints in Eq. (1) can be abstracted into a graph colouring (GC) model [13], based on which channels (colours) can be assigned to transmitters. The corresponding GC model with transmitter-centric constraints for the scenario in Fig. 1(a) is shown in Fig. 1(b). A label on edge $t_i - t_j$ indicates channel(s) unusable simultaneously by transmitters t_i and t_j according to Eq. (1).

B. Receiver-centric Constraints

Although interference constraints for spectrum assignment are typically constructed in a transmitter-centric way to *exclude* co-channel interference, interference actually takes place at the receivers. Based on some SINR requirement, (t_i, r_i) may be able to tolerate some level of interference while maintaining admissible communication. Referring to the network in Fig. 1(a), transmitter-centric constraints would forbid transmitters t_1 and t_3 to use channel A simultaneously. However, r_1 (r_3) may be sufficiently far from t_3 (t_1) such that even if t_1 and t_3 both use channel A, the resulting SINR at r_1 and r_3 may be sufficiently high to permit admissible communication quality.

Hence, by allowing additional interference at each receiver, receiver-centric constraints can potentially support additional communication links in each receiving node's vicinity for a given spectrum availability, giving rise to improved spectrum utilization. This has been demonstrated in simulation results presented in [10], [11]. Due to space constraints, we refer interested readers to [12] for full details on methods of generating constraints and evaluating conflict-free assignments.

III. RECEIVER-CENTRIC INTERFERENCE MANAGEMENT FOR MAC IN CDMA UASNS

Let us consider a CDMA acoustic sensor network in Fig. 2 with N communicating pairs at chip rate W kcps. Assume that (transmitting) node t_i transmits to (receiving) node r_i at power level (and with code) $P_i(c_i)$ at data rate R_i kbps. To achieve a target error probability corresponding to a given Quality of Service (QoS), it is necessary that the energy-per-bit to noise-density ratio at node r_i, $(\frac{E_b}{N_0})_i$ satisfies some threshold ϵ, i.e.,

$$(\frac{E_b}{N_0})_i = \frac{W}{R_i}\frac{P_i(c_i)\Gamma_i}{\eta + \alpha I_i^{oc} + I_i^{cc}} \geq \epsilon, \tag{2}$$

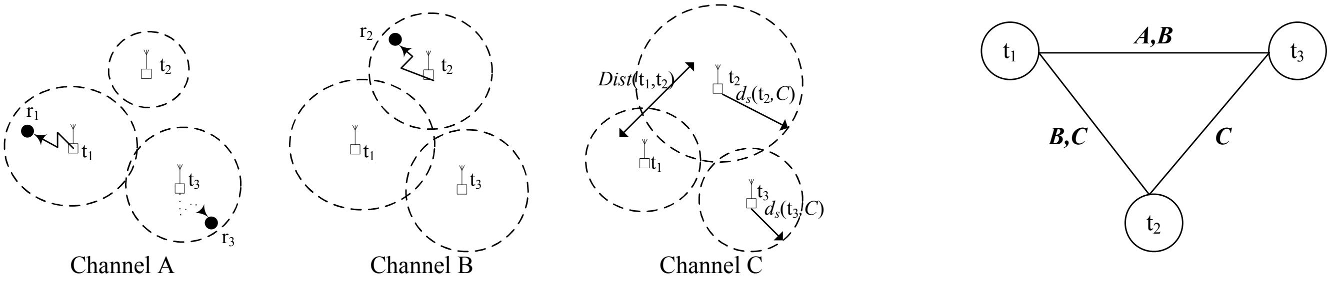
where η is the receiver noise floor, Γ_i denotes the attenuation due to path-loss between t_i and r_i, I_i^{cc} is the co-code interference power, I_i^{oc} is the off-code interference power at node r_i and α is the code non-orthogonality factor. These interference terms can be expressed as follows:

$$I_i^{cc} = \sum_{j \neq i, c_j = c_i} P_j(c_j)\Gamma_{j,i}$$
$$I_i^{oc} = \sum_{j \neq i, c_j \neq c_i} P_j(c_j)\Gamma_{j,i},$$

where $\Gamma_{j,i}$ is the attenuation due to path-loss between t_j and r_i. By regulating these interference terms through appropriate code assignment and transmit power control, the QoS requirement given in Eq. (2) can be satisfied, giving rise to *admissible* communication quality for (t_i, r_i).

Our objective in this paper is to apply constraint-based interference management to assign $\{P_i(c_i)\}_{i=1}^N$ such that the QoS requirement is satisfied for all N communication pairs, i.e., $(\frac{E_b}{N_0})_i \geq \epsilon\ \forall\ i$, with the *minimum* energy per bit, $\sum_{i=1}^N \frac{P_i(c_i)}{R_i}$, and a *minimum* number of codes.

While transmitter-centric constraints have been used for transmitter-based code assignment [6] in CDMA terrestrial networks, they exclude *any* MAI and are therefore inefficient. While the solution of receiver-centric interference constraints [12] may offer a more effective MAC, nonzero cross-correlation amongst codes introduces additional interference, leading to more restrictive interference constraints. While MAC in FDMA/TDMA networks can be reduced to the one-dimensional problem of channel/time-slot assignment, the near-far problem necessitates the joint assignment of both code and transmit power in CDMA networks, which increases the complexity of the constraint generation and solution. However,



(a) Transmitter-centric interference constraints

(b) Colour-sensitive Graph Coloring Model

Fig. 1. (a) An illustration of transmitter-centric interference constraints and (b) the corresponding colour-sensitive graph colouring model for allocating 3 channels, $\{A, B, C\}$ amongst 3 transmitting users, $\{t_1, t_2, t_3\}$ (represented by vertices). Each dotted circle represents the interference range of a node and the label on edge *i*−*j* indicates spectrum unusable by nodes *i* and *j* simultaneously.

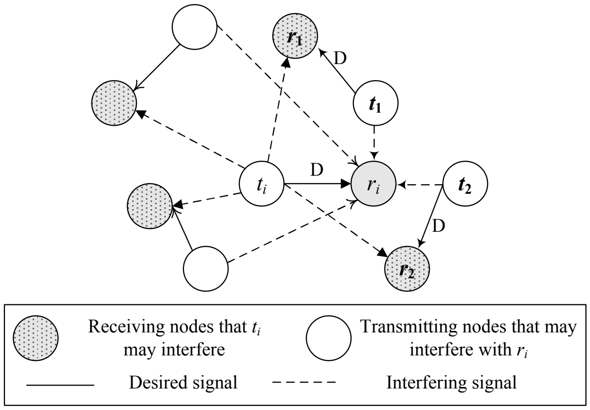


Fig. 2. Illustration of potentially interfering transmitters and potentially-interfered receivers due to communication pair (t_i,r_i) in CDMA Underwater Acoustic Sensor Networks.

due to the high deployment and equipment costs, UASNs tend to be *sparse* [2], which renders MAC using receiver-centric constraints a tractable and practical approach.

A. Constraint Representation

Let us consider the CDMA UASN in Fig. 2. For each receiver r_i, we define its *scope* S_{r_i} [9] as the list of transmitters that will contribute to its energy-per-bit to noise-density ratio and therefore interfere. Quantitatively, $\forall j \neq i$:

$$j \in S_{r_i} \Leftrightarrow \begin{cases} P_j(c_j)\Gamma_{j,i} \geq \eta, & c_j = c_i; \\ \alpha P_j(c_j)\Gamma_{j,i} \geq \eta, & c_j \neq c_i. \end{cases}$$

Therefore, given $P_i(c_i)\ \forall\ i$, we can construct S_{r_i}, which is similar to the receiver-centric model employed for interference management in terrestrial wireless networks [10]. Unlike the orthogonal channels modelled in that scenario however, use of CDMA MAC means that even off-code interferers will be contributing to the interference of all receivers whose scopes they occupy.

Remark 1: In general, interference constraints can be represented as *tuples* [9], [12] and solved to obtain conflict-free assignments in an efficient manner. These per-receiver tuples represent the edge cases of the maximum number of co-code vs off-code interfering transmitters allowable, against which a given assignment may be compared to check for a violation. While this representation is not necessary for the small and sparse networks simulated in this study, it may be required as the network expands and becomes more connected, when the confirmation that a given assignment is within constraints over each receiver's scope becomes a more complicated calculation.

Remark 2: Similarly, the condition $P_j(c_j)\Gamma_{j,i} \geq \eta$ is used to compute the detection range, $d_s(t_j)$ of t_j, from which pairwise transmitter-centric interference constraints can be constructed according to Condition 1.

B. Evaluation of Conflict-free Assignments

Next, we solve the constraints to obtain conflict-free assignments of code/power for each transmit-receive pair. We consider a two-stage iterative algorithm for joint power and code assignment that comprises (i) a code assignment block and (ii) a power optimization block, as illustrated in Fig. 3.

1) Code Assignment ($P_i(c_i)$ = P_i): We assume an initial power assignment ($P_i(c_i) = P_i$), and without loss of generality, we assume that $P_i = P$. In order to construct a code assignment we use a sub-optimal heuristic algorithm based on that proposed in [13] to guarantee required QoS as in Eq. (2). On a transmitter by transmitter basis codes are assigned, once checked to ensure they do not violate the $\frac{E_b}{N_0}$ of any receiver affected by the assignment (i.e., any containing this transmitter within their scopes).

2) Power Optimisation: Using the initial code assignment obtained based on an initial power assignment P, it is now possible to evaluate the surplus of $(\frac{E_b}{N_0})_i$ over ϵ for each receiver, and reduce P_i by a corresponding amount. This will in turn affect the $\frac{E_b}{N_0}$ of all receivers with which t_i is interfering, possibly allowing their corresponding transmitters to reduce the power in turn. As such the power assignment may be improved iteratively, with each iteration converging towards a pseudo-optimal power assignment.

With each iteration a new code assignment may also be performed, as reductions in transmit power may cause sufficient

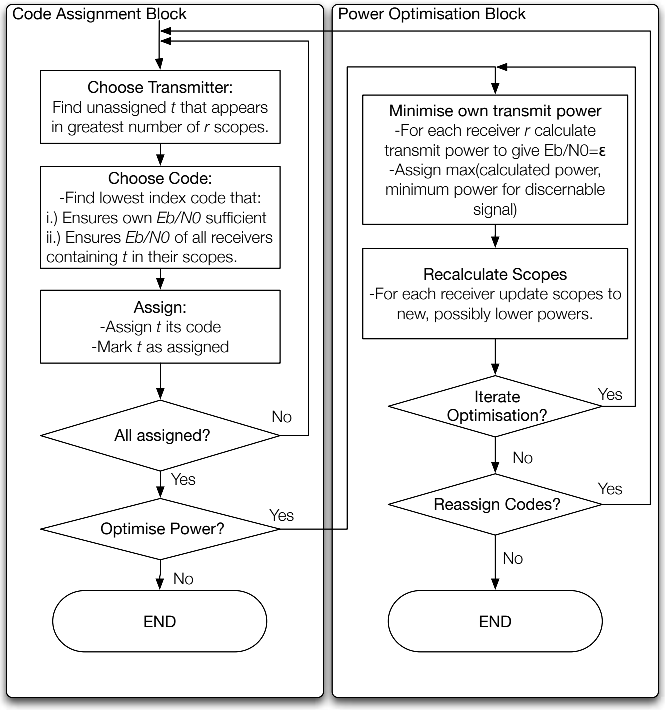


Fig. 3. Flowchart showing the code assignment and power optimisation algorithms.

change in some receivers' scopes to allow additional co-code interference.

IV. Simulation Results

We demonstrate the performance of our proposed algorithm for joint power/code assignment through numerical simulation. We consider a 3-D CDMA UASN with the network parameters specified in Table I. We assume Thorp's attenuation model for shallow water environment [14], where the attenuation due to path loss is given as follows:

$$\Gamma_{j,i} = \frac{1}{Dist(t_j,r_i)^2[m]10^{\frac{(\beta Dist(t_j,r_i)/1000+A)}{10}}},$$

where $A = 5$ dB is the transmission anomaly to account for multipath, refraction, diffraction and scattering and β is Thorp's expression for medium absorption coefficient given by:

$$\beta[dB/km] = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75\times10^{-}5f^2 + 0.003.$$

Within a 3-D region of 30×30×30km, N transmitters are randomly located, where $10 \leq N \leq 100$. Then a receiver corresponding to each transmitter is randomly placed within the communications range as determined by the attenuation model, and accepted as valid if the sum total of all detectable off-code interference does not cause $\frac{E_b}{N_0}$ to drop below ϵ. This condition ensures that all transmit-receive pairs can at least maintain admissible communication quality under the most favourable interference conditions, which allows for a fair comparison between our proposed receiver-centric algorithm and conventional transmitter-centric techniques.

Parameter	Value
f	33 kHz
W	19.2 kcps
R	2.5kbps
ε	2 dB
η	$3.1473\text{x}10^{-17}$W
$P_{r,thresh}$	-94 dBm

TABLE I
System parameters used to illustrate various interference management approaches for MAC in CDMA UASNs.

A. Code Assignment ($P_i(c_i) = P$)

We compare the number of codes required by an assignment taking into account receiver-centric constraints with one based on transmitter-centric constraints, assuming an initial power assignment of P=1W. The results, averaged over 100 randomly generated topologies for each N, are plotted in Fig. 4. We note that receiver-centric constraints require a consistently lower number of codes. We can further note that as the network scales, the number of codes required for a transmitter-centric assignment increases much more rapidly than our proposed receiver-centric approach.

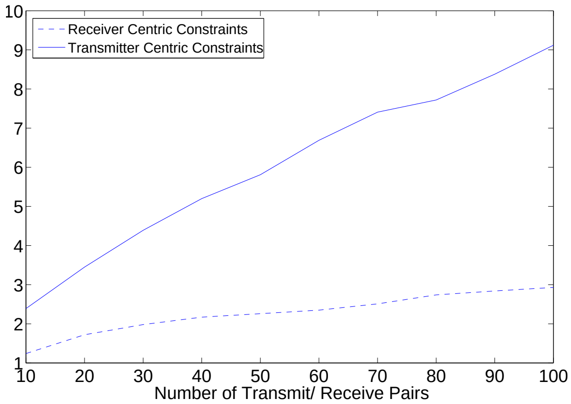


Fig. 4. Number of codes required vs number of transmit-receive pairs (N), for code assignment using receiver-centric and transmitter-centric constraints (P_i = 1W).

B. Joint Code/Power Assignment

Next, we examine the convergence of our iterative two-stage algorithm for joint code/power assignment. We graph the per-node transmit power (averaged over all transmitters) after each iteration for N = 20, 50 and 80, again over 100 randomly generated topologies for each N, in Fig. 5. We can see that average transmit power converges close to its pseudo-optimal in only a small number of iterations, usually ≤ 10. Furthermore, we note the significant drop in average transmit power, from 30dBm (1W) to less than 15dBm achieved with power optimisation.

Next, we quantify the improvement in the minimum number of codes required following 10 iterations of power optimisation. The results are plotted in Fig. 6. For purposes of comparison, we also generate code assignments using transmitter-centric constraints, before and following the power optimisation. We note that while there is an improvement in the number of codes required for transmitter-centric constraints following the power optimisation, receiver-centric constraints continue to offer superior code assignment efficiency.

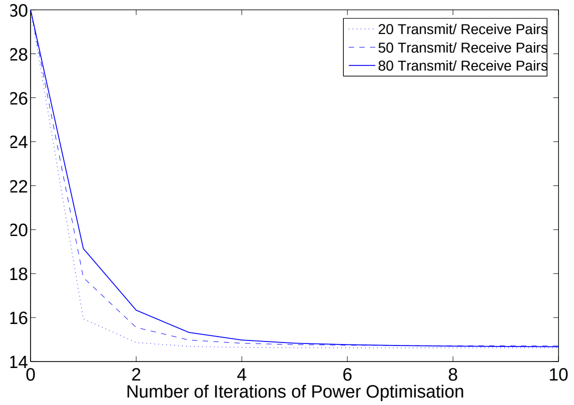


Fig. 5. Average Transmitter Power vs Number of iterations of Optimisation.

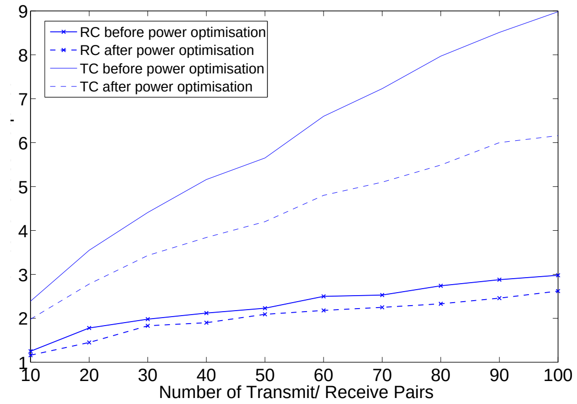


Fig. 6. Number of codes vs number of transmit-receive pairs without and with power optimisation (10 iterations) for joint code/power assignment with transmitter-centric (TC) and receiver-centric (RC) constraints.

V. CONCLUSIONS AND FUTURE WORK

A major challenge for the deployment of underwater acoustic sensor networks (UASN)s is the development of a MAC protocol suited for the underwater environment to enable a wide variety of applications. We propose the use of receiver-centric interference constraints for joint code/power assignment which more realistically models interference constraints for CDMA, accounting for code non-orthogonality and the near-far problem prevalent in CDMA networks. Through numerical simulations, we demonstrate the significant gains achievable in terms of code and power efficiency when compared with conventional overly-conservative transmitter-centric constraints, when used for joint code-power assignments.

Future work may involve generalisation of the tuple representation of receiver-centric constraints to two-dimensions. This takes into account both power and code simultaneously in the constraint generation, and may result in more efficient conflict-free assignments compared to our proposed two-stage algorithm.

In addition, a comparison with optimal assignment obtained using Mixed and Integer Linear Programming methods would allow tractable evaluation of the level of sub-optimality due to our choice of a sub-optimal heuristic for conflict-free assignment.

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