Wireless Multimedia Networks: Cross-Layer Access Protocols Based on Sequential Opportunistic Decoding (SOD)

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O. Jegbefume, M. Saquib, M. Tacca, A. Fumagalli, P. Monti
The Erik Jonsson School of Engineering and Computer Science
The University of Texas at Dallas
Richardson, TX 75080, USA
{oxj013000, saquib, mtacca, andreaf, paolo}@utdallas.edu

Abstract

Spread spectrum (SS) solutions offer well understood advantages to wireless networking, e.g., robustness to noise and interference, concurrent asynchronous transmissions, effective power and transmission rate control mechanisms. One of the authors' recent advances in this field makes it possible to take SS solutions to the next performance level, i.e., *sequential opportunistic decoding*, or SOD for short. SOD is based on transmitting data symbols multiple times within the frame using non-orthogonal partial signature waveforms or mini-frames. Depending on the received instantaneous signal-to-interference-plus-noise ratio (SINR), a given subset of such mini-frames may suffice to reliably decode the data symbols. The best performing subset contains mini-frames that are received under better-than-average SINR channel conditions — i.e., these are referred to as the opportunistic mini-frames. By instantaneously controlling the number of mini-frames transmitted, SOD also offers *distributed adaptable processing gain*.

The objective of this report is to propose cross-layer medium access control (MAC) protocols based on SOD. These protocols are especially suited to operate in a crowded radio spectrum, e.g., when multiple WLANs and/or wireless sensor networks coexist in the same radio space, possibly supporting multimedia applications. This unique advantage originates from the integration of two sub-layers. The lower sub-layer (SOD-MAC) applies the SOD adaptable processing gain to contain both the level of interference in the radio channel and network latency. It also minimizes the power consumption at the node and supports multiple classes of service. The upper sub-layer (ARQ-MAC) enables statistical multiplexing of an unbounded number of attempts of frame transmission generated by uncoordinated active nodes and it provides the automatic retransmission request (ARQ) capabilities.

In essence, the uniqueness of these cross-layer access protocols is their ability to achieve efficient statistical multiplexing of traffic generated by uncoordinated nodes while containing the level of interference in the radio channel. The challenge is to combine frame retransmission schemes and SOD adaptable processing gain strategies in the most effective way, while keeping the access protocols in the stable region. The payoff is the ability to: increase the radio channel utilization, contain network latency, reduce energy consumption at the wireless node, and provide a QoS platform for both real-time and datagram traffic.

Index Terms: Spread Spectrum communications, Cross Layer design, Multimedia, Access Protocols, Adaptive Processing Gain.

I. Introduction

Support for multimedia in wireless data networks (WLAN and Sensor) continuously gains momentum [1]–[3]. In the coming years, crowded areas with large numbers of wireless nodes (both mobile users and sensors) are expected to be a common reality [4]. It is a must for the wireless technology to find a viable and practical way to deal with both the coexistence of multiple uncoordinated active nodes in the same area and the associated quality of service (QoS) requirements. The interference signal is a serious obstacle exacerbated by distinct networks that coexist in the same radio space. Several current solutions combat the interference problem by means of various forms of data "redundancy", e.g., incremental redundancy Hybrid Type II ARQ protocols based on rate-compatible punctured convolutional (RCPC) codes [5]. Power consumption is also a concern for possibly a large population of wireless nodes.

The objective of this report is to propose cross-layer medium access control (MAC) protocols — which combine two sub-layers — proving that they are a viable solution to deal with the challenges associated with wireless multimedia networks in crowded areas. The lower sub-layer (SOD-MAC) is based on spread spectrum (SS) with sequential opportunistic decoding (SOD). SS is chosen as it provides robust communication and multiple concurrent access in the form of semi-orthogonal channels defined by unique codes (CDMA) [6]. SOD [7] is chosen as it provides *distributed adaptable processing gain* — when sending information over the radio channel — to minimize power consumption at the node, minimize the level of interference in the radio channel, create classes of service, among other features. As explained in Section II, the SOD-MAC protocols have the potential to transmit "just enough redundancy" (JER) over the radio channel to get the job done. The upper sub-layer (ARQ-MAC) enables the statistical multiplexing of an unbounded number of frame transmission attempts generated by uncoordinated active nodes, as it provides the automatic retransmission request (ARQ) capabilities that are required when the desired QoS is not reached by individual frames. For example, error-free frame decoding at the receiver may be prevented by a strong interference signal due to too many concurrent frame transmission attempts. In essence, the uniqueness of the proposed cross-layer access protocols is their ability to yield efficient statistical multiplexing of traffic generated by uncoordinated nodes while containing the level of interference in the radio channel thanks to the adaptable processing gain of SOD.

Once successfully designed and implemented, the cross-layer access protocols based on SOD represent a valid solution for wireless multimedia networks in crowded areas as they support:

1) increased number of concurrent real-time streams with guaranteed maximum frame error rate (FER),
2) increased reliable datagram throughput,
3) contained network latency,
4) energy efficient transmission/reception at the wireless node, and
5) QoS for both real-time and datagram traffic.

Combined with the other widely known advantages of SS, these five properties make the cross-layer access protocols based on SOD a competitive solution with a potentially significant impact on future wireless technology, complementing the already existing solutions (Section IV).

The next section defines the concept of JER in a wireless access protocol. It then describes how SOD aims at achieving JER, and how it can be harnessed into a cross-layer access protocol. Two alternative cross-layer access protocol families are then presented (Section III), underlining their respective open challenges that must be overcome.

II. The Just Enough Redundancy Concept and the SOD Approach

This section illustrates graphically the concept of JER and explains how SOD accomplishes it in a simple way.

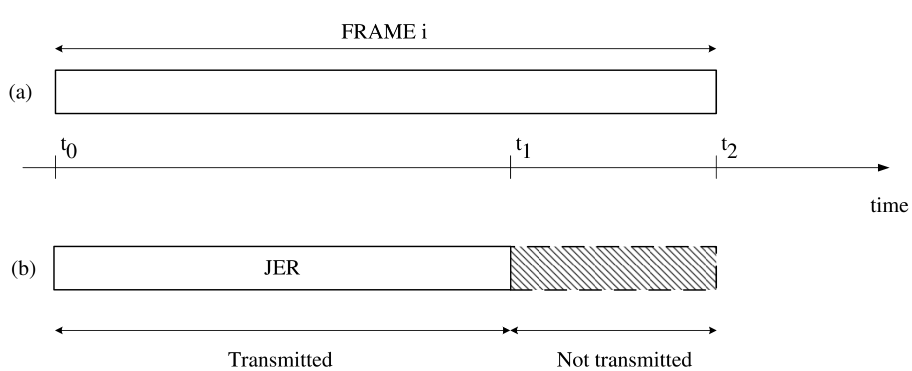

Fig. 1. Single frame transmission: (a) conventional, (b) JER.

Consider a radio channel with multiple concurrent data frame transmissions, whereby each transmission uses a dedicated code from a set of semi-orthogonal codes. Consider one of such frames as it is reaching the intended receiver. In conventional solutions, the frame must be received completely, then decoded to determine if the received data set is error-free. This case is illustrated in Figure 1(a), whereby frame i is entirely received and decoded at time t_2.

Imagine now a frame that, as it is being received, at every time instant delivers to the receiver some amount of incremental redundancy on the *entire* data set. The receiver continuously decodes the incoming frame till "just enough redundancy" becomes available to overcome the interference signal level at that moment. Imagine then that the frame transmission is immediately interrupted at that moment, as delivering the remaining part of the frame would not provide any additional benefit to the receiver. Figure 1(b) illustrates this case, whereby the transmitted data set is decoded successfully at t_1. The shaded region indicates the frame portion that need not be transmitted/received.

Figure 2 compares the JER frame transmission (b) against the Hybrid Type II ARQ protocol (a). In (a), the data set is first transmitted using frame i. The frame is not decoded successfully by the receiver at t_1. After a timeout and possibly a backoff time the data set is transmitted a second time using frame ii to provide incremental redundancy. Frames i and ii are then jointly decoded successfully at t_5. In (b) a single longer frame is transmitted that contains the same amount of redundancy carried by both frame i and ii. The frame is decoded successfully by the receiver at t_2, i.e., as soon as JER is received. The shaded region indicates the frame portion that need not be transmitted/received.

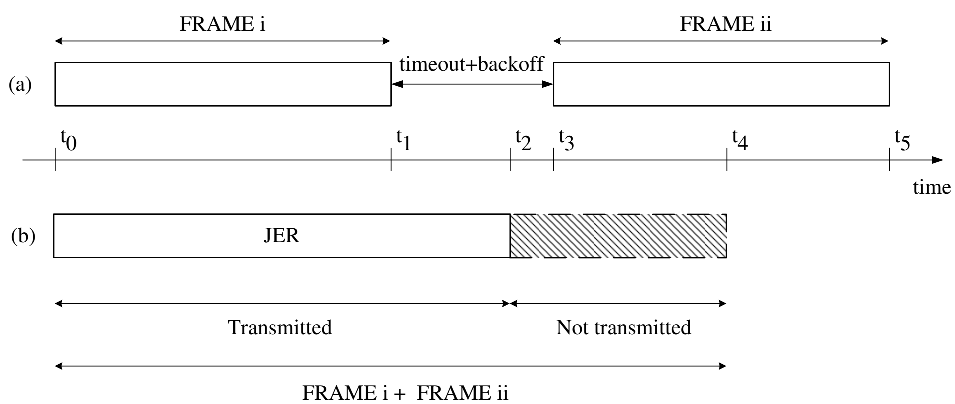

Fig. 2. (a) Hybrid Type II frame retransmission, (b) JER.

From the above examples the outcome of the JER solution is quite straightforward: it saves radio bandwidth — available to other frame transmissions and/or for reduced interference level — it saves energy at the transceiver, and it reduces the transmission latency.

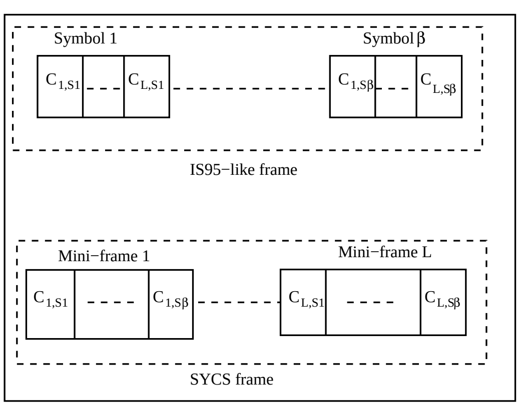

Fig. 3. IS95-like and SYCS frame structures.

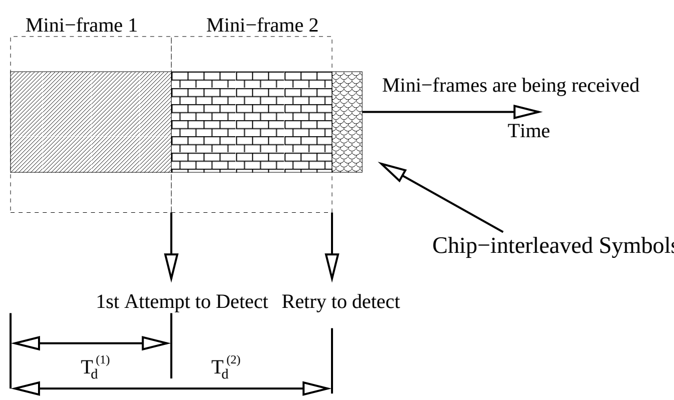

Fig. 4. SOD in SYCS.

The next step is to describe how SOD offers a simple way to achieve a form of JER (albeit not as in an ideal manner as described above) using distributed adaptable processing gain. For sake of clarity, SOD is described using the *system with chip-interleaved symbols* (SYCS) framework[1].

The SS conventional (similar to IS95 [6] (IS95-like)) frame structure is shown in the upper part of Figure 3. A total of β data symbols are coded sequentially. Blocks of signature chip sequences $\{C_{i,j}\}$ are used to transmit the data symbols. The processing gain (chips per symbol) is L. The entire frame must be received to attempt to decode all β symbols (case (a) in Figure 1).

The lower part of Figure 3 shows the frame structure used in SYCS [9]–[11]. Chip sequences belonging to the data symbols are interleaved to take advantage of time diversity during the frame transmission. The resulting blocks of chip sequences are called mini-frames. SOD makes use of the mini-frames structure in an intriguing way, i.e., decoding may be attempted using a subset of the mini-frames. To accomplish SOD two criteria must be met.

Criterion 1: each data symbol must be repeated multiple times within the frame (e.g., using the mini-frames in SYCS). Criterion 1 allows SOD to decode a frame sequentially within the transmission time of that frame.

Criterion 2: system implementation should not depend on the orthogonality of the partial signature waveforms used to transmit the symbol multiple times. Criterion 2 is essential because under SOD, decisions on symbols will be attempted using only part of the frame, i.e., a subset of the signature waveforms. A natural way to fulfill criteria 1 and 2 is to adopt direct-sequence (DS) SS technology, such as DS-CDMA, or DS ultra-wide band (UWB).

For decoding, the subset of mini-frames can be chosen in various ways. For example, the mini-frames are sequentially combined with one another in the order they are received until either a reliable decision about the data symbols is made, or the end of the frame is reached (case (b) in Figure 1). Note that error detection capability is provided by the cyclic redundancy code (CRC) bits in the data symbols [12].

More in general, the subset of the mini-frames that are combined to attempt decoding can be any, the best one containing mini-frames that are received under better-than-average signal-to-interference-plus-noise ratio (SINR). These are the opportunistic mini-frames (shaded in Figure 5).

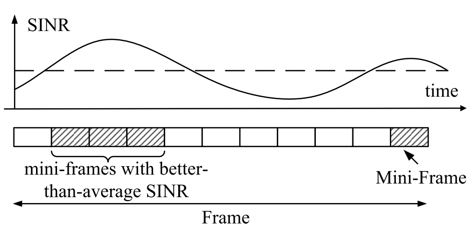

Fig. 5. SOD with fixed processing gain.

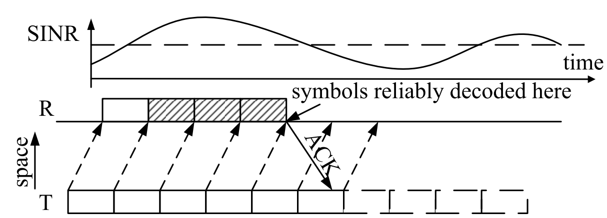

Fig. 6. SOD with adaptable processing gain.

Theoretical results predict that the use of SOD with *fixed processing gain* (SOD-FPG) — i.e., a constant number of mini-frames is always transmitted (Figure 5) — may yield substantial performance gains, e.g., SOD reaches FER= 2.5×10^{-3} with 10 active users, compared to FER= 1.6×10^{-2} of the SS conventional solution (see Sections V). Results also predict that the use of SOD *adaptable processing gain* — i.e., only the mini-frames required to achieve JER are transmitted (Figure 6) — may further ameliorate performance, e.g., FER= 2×10^{-4}, due to the reduction of the interference level. One further advantage of SOD is that adaptable processing gain is achievable by varying the number of transmitted mini-frames and without having to change the transmitted instantaneous power level. This feature may alleviate the transceiver hardware complexity and offer a software controllable solution to achieving adaptable processing gain.

While the SOD concept has been studied extensively for fixed processing gain — primarily for IS95 applications — the adaptable processing gain of SOD is not yet fully understood at this time. More

[1]As shown in [7], [8], SOD may be applied to parallel sequences too.

specifically, it remains to be seen how this technique can be harnessed by specifically designed access protocols and become of practical use in a variety of other wireless network applications.

III. Cross-Layer Access Protocols Based on SOD

As already mentioned, the access protocol must address two key functions, namely, embedding the adaptable processing gain of SOD (the SOD-MAC sub-layer) and providing the ARQ capabilities (the ARQ-MAC sub-layer), which are required to cope with the unbounded number of frame transmission attempts generated by uncoordinated active nodes. For simplicity, it is assumed that each active node is assigned a unique code for its own frame transmissions[2]. It is also assumed that there is no access restriction across the uncoordinated active nodes.

When the interference signal strength prevents the receiver from achieving the desired QoS at the end of the first frame transmission, the cross-layer protocol must decide how to react. Should the SOD processing gain be increased (transmitting more mini-frames per frame)? Or should the frame be retransmitted more times, keeping constant the number of mini-frames? Note that while both actions represent potential remedies, they may lead to network instability due to an escalation of every node's reaction to an increasingly stronger interference signal (see Figure 9 in Section VI). Appropriate backoff mechanisms must be devised to keep the protocol in the stable region.

When the interference signal is weak, the cross-layer protocol must decide how to take full advantage of this circumstance. Should the SOD processing gain be decreased, and by how much? A good balance must be found in this case to further lower the interference signal level if possible and to contain the energy consumption at the wireless nodes.

In substance, the challenge here is to identify the strategy for jointly adjusting the optimal frame size and the retransmission backoff mechanism, to make them work together towards a common performance goal. Note that an additional challenge is represented by the possibility of distinct networks that may run their own access protocols and coexist in the same radio space. As these networks may interfere with one another, their respective protocols must be designed to efficiently coexist, without necessarily resorting to direct coordination. All the above must also take into account QoS requirements, e.g., different classes of FER for real-time traffic and different classes of latency for datagram packets. Service differentiation may be achieved here by using multiple processing gains in conjunction with more or less aggressive retransmission schemes.

Two families of cross-layer access protocols with adaptable processing gain are discussed next:

- SOD-IF: a high risk, high reward approach to accomplish JER with *instantaneous feedback*,
- SOD-DF: a lower risk solution from the hardware viewpoint, which requires smarter access protocols to retain most of the JER offered advantages via *delayed feedback*.

A. *SOD-IF Access Protocols*

In SOD-IF access protocols the receiver attempts decoding on the fly while receiving the mini-frames (Figure 6). When the decoding attempt is successful, a short acknowledgment (ACK) is immediately sent. Upon receiving the ACK, the transmitter interrupts the frame transmission. In SOD-IF the length of the transmitted frame depends on prior channel and interference conditions. As a result, SOD-IF provides instantaneously adaptable processing gain, saves transmit power and reduces symbol interference. To be efficiently implemented, SOD-IF requires real-time decoding of the incoming mini-frames and immediate ACK transmission. In addition, the entire frame transmission time is required to be longer than the link round trip propagation delay plus the decoding processing time at the receiver. Recent advances in VLSI [13] and signal processing technologies indicate that the processing time of the channel decoder will be reduced significantly in the near future.

[2]Other scenarios that may be more realistic will be studied in the project, whereby a code may be shared by multiple nodes.

Anticipated challenges include the design of fast sequential algorithms to sub-optimally decode the received mini-frames in real-time. Objective functions include computational complexity, channel capacity, latency, transmission power, and reliability. Full duplex transmission is required to send the ACK that may be used to shorten the frame transmission time. A viable solution for SOD-IF must be identified and proved using both hardware and software demonstrators, which will determine the practicality and cost effectiveness of SOD-IF.

B. SOD-DF Access Protocols

The SOD-DF access protocols represent an alternative to SOD-IF and they may be required when either the link round trip propagation delay is high or SOD-IF is not cost effective. In SOD-DF the number of mini-frames to be transmitted is determined prior to the frame transmission and is based on the delayed feedback from the receiver. Thus, the receiver does not need to stop the frame transmission, which relaxes both the transceiver hardware requirements and the time constraint on the decoding algorithms.

The main challenge here is to be able to guess, frame by frame, the optimal frame length (or amount of processing gain) by making use of the delayed feedback from the receiver. It is expected that this solution works reasonably well in a slow fading channel. Applications in fast fading channel may be more challenging and will require careful study. Hardware and software demonstrators are required to test SOD-DF and show its viability under various fading conditions.

Before rigorously presenting some of the SOD performance gains and problem formulations, a short survey of the state-of-the-art in the field of wireless networks is presented next.

IV. Previous Work

This section provides an overview of the existing access protocols, with special emphasis on their QoS support, used in today's wireless local (WLAN), metropolitan (WMAN), and sensor networks (WSN).

With the convergence of voice, video, audio, data and message services it is necessary to have wireless access protocols supporting multimedia applications. Unlike conventional voice traffic, multimedia traffic may be bursty with data rates varying a lot during the connection span [1]. Another obstacle is represented by the coexistence of multiple wireless networks and devices in the same area, the so called crowded spectrum issue [4].

For this reason, a well designed wireless access protocol for multimedia applications should provide a way to: (i) make an efficient use of the limited resources, i.e., bandwidth and energy, (ii) treat packets from various applications based on their QoS constraints, and (iii) deal with interference caused by multiple active connections in the same radio space.

The most commonly used standard in WLANs is IEEE 802.11 (WiFi). The MAC of WiFi has two modes of operations: distributed coordination function (DCF) and point coordination function (PCF) [1]. When operating in DCF mode, the WiFi MAC does not define class/service differentiation. DCF uses contention-based media access control protocol (CSMA/CA), and all traffic in a node is queued and transmitted in a first-in-first-out (FIFO) order. Therefore DCF guarantees a best effort QoS service level which is suitable for non-real time applications. When operating in PCF mode, the WiFi MAC does not define class/service differentiation either. PCF uses a polling-based media access control protocol and, due to the lack of a classification mechanism within each node, the packet scheduling at a node still uses a FIFO mechanism. This makes PCF able to provide a certain level of guaranteed QoS.

MAC enhancements for better QoS support are specified in IEEE 802.11e where class/service differentiation is provided [14]. Up to 8 traffic categories and up to 8 traffic streams are specified to provide prioritized and parameterize QoS, respectively. Based on the priority of the queues, the MAC has different backoff window sizes, i.e., packets with high priority take a quicker backoff than packets in the low priority queues.

The most common standard used in WMANs is IEEE 802.16 (WiMax). The WiMax MAC is connection oriented, i.e., traffic is mapped into connections. This provides the ability to request bandwidth with its associated QoS and traffic parameters for every connection [1]. During uplink transmissions (subscriber to base-station), the subscriber accesses the channel in a TDMA fashion. During downlink transmissions (base-station to subscriber), data packets are transmitted by the base-station to all subscribers and a subscriber picks up only its own packets. Upon the request of a connection from the subscriber, the base-station provides the subscriber with access slots (time slots to send data). Once a time slot is assigned, the subscriber is allowed a minimally guaranteed access to the base-station. The length of time slots can shrink or enlarge during the connection period. The standard defines four types of service flows to provide QoS support: (i) Unsolicited Grant Service (UGS) - supports real-time data streams with fixed packet size issued at regular intervals e.g., VoIP, (ii) Real Time Polling Service (RTPS) - supports real time data streams with variable packet size issued at regular intervals e.g., MPEG Video, (iii) Non Real Time Polling Service (NRTPS) - supports delay tolerant data with variable packet size, for which a minimum data rate is specified e.g., FTP, and (iv) Best Effort (BE) - supports data streams where no minimum service is required and packets are handled on a space-available basis. Each service flow comes with a set of QoS parameters specified during the connection subscription at the base-station. Examples of QoS parameters are: Minimum reserved traffic rate, Maximum latency, etc.

MAC solutions for WSN have received intense research attention. Table I presents a list of solutions and shows which are the protocols able to guarantee Multimedia/QoS support.

TABLE I
ACCESS PROTOCOLS AND MULTIMEDIA/QOS SUPPORT FOR WSN.

MAC Protocol	**Multimedia/QoS Mechanism**
LMAC [15]	Yes, TDMA
S-MAC [16]	Yes, node scheduling tables
TMAC [17]	No
LEACH [18]	No
B-MAC [19]	No
PMAC [20]	Yes, TDMA
BitMAC [21]	No
Reservation MAC [22]	Yes, slot reservation based on priority and demands
Q-MAC [23]	Yes, priority differentiation of network services
Adaptive Low Power Reservation Based MAC [24]	Yes, contention based slot reservation and transmission

The authors in [25] characterize analytically the multiaccess interference in wireless CDMA [6], [26]–[37] sensor networks with uniformly random distributed nodes and study the trade off between interference and connectivity. The work in [18] provides a combined TDMA/CDMA based MAC approach. Each node communicates with a dynamically elected cluster head using a TDMA scheme. Cluster heads communicate with the remote destination directly using a CDMA approach. The authors in [38] propose a detailed analysis of minimum energy (ME) and modified minimum energy (MME) coding in CDMA WSNs. The analysis is carried out in terms of radio power consumption and energy consumption of the electronic circuit transceivers. The work in [39] presents the design and evaluation of a self-organizing, location-aware MAC protocol for DS-CDMA based sensor networks. The authors in [40] propose a CSMA-based MAC protocol, designed specifically to support the periodic and highly correlated traffic of some sensor network applications. They propose an adaptive transmission rate control (ARC) scheme, whose main goal is to achieve media access fairness by balancing the rates of originating and route-through traffic. The work in [41] investigates the efficient scheduling and the power allocation problem for a delay constrained CDMA WSN. The total transmit power is minimized, while the SINR target is satisfied at all cluster heads and at the sink.

Some recent works (e.g., [42], [43]) attempt to design centralized schemes for assigning rates to users based on their average link-qualities. However, none of the existing solutions exploits the adaptivity to the instantaneous channel condition of the proposed cross-layer access protocols based on SOD while providing QoS. Note that the proposed protocols are distributed protocol that allocate the rate (equivalently, processing gain) to a user based on both instantaneous channel and interferences conditions. The potential advantages of using the SOD mini-frame approach are discussed in the next two sections.

V. Analysis of SOD-MAC Protocols

FER Analysis of SOD-FPG. The frame error rate (FER) analysis is carried on using a simplified SOD protocol with fixed processing gain termed SOD-FPG (Figure 5). The SOD-FPG protocol works in the following way. Differently from SOD-IF and SOD-DF, the transmitter always transmits all N mini-frames, i.e., the entire frame. Multiple decoding attempts are sequentially performed at the receiver. Let n be an integer, counting the number of attempts made at any given point. The maximum number of attempts $n \leq N = T_f/T_d$ is an integer, where T_f is the frame duration and T_d denotes the time interval between attempts. Decoding attempts are performed according to the following rule:

- *Step 1:* Set $n = 1$
- *Step 2:* IF $n > N$, THEN frame cannot be detected and STOP
- *Step 3:* Observe the received mini-frames over the interval $[0, T_d^{(n)})$,
- *Step 4:* Decode the data symbols along with CRC bits from the received mini-frames,
- *Step 5:* IF an error is detected using CRC, THEN set $n = n + 1$ and GOTO Step 2, ELSE STOP.

Data symbols are uncoded, i.e., CRC and RCPC are not used. Let W_n be a binary variable that represents the outcome of the n^{th} decoding attempt. $W_n = 1$ if the frame is reliably decoded at the n^{th} attempt, $W_n = 0$ otherwise. The probability mass function (PMF) of W_n is given by

$$P(W_n) = \begin{cases} P_f(n) & W_n = 0 \\ 1 - P_f(n) & W_n = 1 \\ 0 & \text{otherwise} \end{cases}, \tag{1}$$

where $P_f(n)$ is the probability of frame error at the n^{th} attempt without knowledge of the outcome of the $n-1$ previous attempts. Let random variable Z_n be defined as

$$Z_n = \sum_{i=1}^{n} W_i. \tag{2}$$

Generalizing, the probability that the frame is still erroneous after n decoding attempts is given by

$$P\left(W_i = 0 \,\forall\, i \geq 1, i \leq n\right) = P\left(Z_n = 0\right) \;=\; \prod_{j=1}^{n} P\left(W_j = 0 | Z_{j-1} = 0\right). \tag{3}$$

In case of an additive white Gaussian noise (AWGN) channel, the value of $P(W_i = 1, Z_{i-1} = 0)$ for $i = 1, \ldots, N$ is obtained performing a nested integration over exponential functions — Gaussian probability density functions (PDF). From probability theory

$$\begin{aligned} P(W_i = 0) &= P\left(W_i = 0 | Z_{i-1} = 0\right) P\left(Z_{i-1} = 0\right) + P\left(W_i = 0 | Z_{i-1} \neq 0\right) P\left(Z_{i-1} \neq 0\right) \\ &\geq P\left(W_i = 0 | Z_{i-1} = 0\right) P\left(Z_{i-1} = 0\right) = P\left(Z_i = 0\right). \end{aligned} \tag{4}$$

From (1) and (4), an upper-bound on the probability that the frame is erroneous after N attempts is

$$P\left(Z_N = 0\right) \leq P(W_N = 0) = P_f(N). \tag{5}$$

The result in (5) indicates that the FER incurred when making N attempts to decode the frame is potentially less than the FER incurred when making just one attempt at the end of the frame.

The mathematical motivation in (5) for using SOD is corroborated by the intuition that due to the time-varying nature of the SINR in wireless channels, a frame that is in error at $n = N$ does not necessarily imply that the same frame is in error at $n < N$.

The increase of computational complexity incurred depends on the number of attempts made to decode the frame. Let $X \in [1, N]$ be the integer random variable that represents either the number of attempts made before a frame is reliably decoded or the end of the frame is reached. It can be shown that the probability that the frame is reliably decoded in the $X = x > 1$ attempt and erroneous in the previous attempts is

$$P(W_x = 1, Z_{x-1} = 0) = P(Z_{x-1} = 0) - P(Z_x = 0). \tag{6}$$

Therefore, the PMF of X can be written as

$$P_X(x) = \begin{cases} 1 - P(Z_1 = 0) & x = 1 \\ P(Z_{x-1} = 0) - P(Z_x = 0) & 1 < x < N \\ P(Z_{N-1} = 0) & x = N \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

The expected value of X is

$$E[X] = 1 + \sum_{x=1}^{N-1} P(Z_x = 0). \tag{8}$$

Noting that $P(Z_x = 0) \leq P_f(x)$

$$E[X] \leq 1 + \sum_{x=1}^{N-1} P_f(x). \tag{9}$$

$E[X]$ is a measure of the SOD-FPG complexity.

FER Analysis of SOD-IF. Assume that the transmitter knows instantly when the frame is reliably decoded at the receiver and stops transmitting the frame. Assume that K is the number of concurrently transmitted frames, e.g., number of users concurrently transmitting. Let K_n be a random variable that denotes the number of frames not yet reliably decoded after attempt n. Therefore, K_N represents the number of frames that are not reliably decoded after N attempts, i.e., at the end of the frame. The probability of frame error after N attempts is

$$\begin{aligned} P'_f &= \frac{E[K_N]}{K} \\ &= \frac{1}{K} \sum_{k_1=0}^{K} \sum_{k_2=0}^{k_1} \cdots \sum_{k_N=0}^{k_{N-1}} K_N P(K_1 = k_1, K_2 = k_2, \ldots, K_N = k_N) \\ &= \frac{1}{K} \sum_{k_1=0}^{K} \sum_{k_2=0}^{k_1} \cdots \sum_{k_N=0}^{k_{N-1}} K_N \left[\prod_{i=1}^{N} \binom{k_{i-1}}{k_i} [P(W_i = 1, Z_{i-1} = 0)]^{k_{i-1}-k_i} \right] [P(Z_N = 0)]^{k_N}, \end{aligned} \tag{10}$$

where $k_0 = K$.

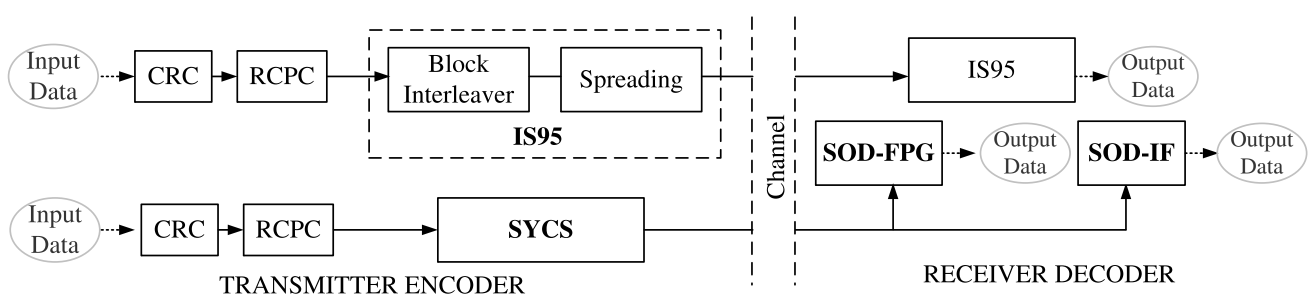

Fig. 7. Encoder and decoder block diagrams.

Numerical Study of SOD-MAC Protocols. The following study case is carried out with the help of simulation. Results compare an IS95 like system to systems based on the SOD-MAC protocols.

The two possible systems are shown in Figure 7. A (120,105) cyclic code with generator vector 102633 (octal) is used for error detection. After passing the data bits through the CRC encoder, the resultant bit string is sent through the RCPC encoder. A (2,1) convolutional code of constraint length 9 (same as the one used in IS95) is adopted. At the output of the RCPC encoder, the frame length is 240 bits. For the SOD-MAC protocols the SYCS encoder described in Section II is used. For the IS95 like system, bit interleaving is performed following the channel encoder, i.e., channel encoded bits are written into a matrix along its columns and read out from its rows. The IS95 block interleaver spans the whole frame duration and has 60 rows and 4 columns. A block fading channel model is used in the simulation, whereby the channel coefficients are statistically described by the Rayleigh probability density function (PDF). A uniform power delay profile is used with a number of paths equal to 2. The number of fades/channel is equal to 4 and processing gain $L = 64$. BPSK signaling with rectangular pulses is used. The signature (chip) sequences are generated randomly for each data symbol. The transmitter power is assigned to achieve the same average SINR for all the received frames.

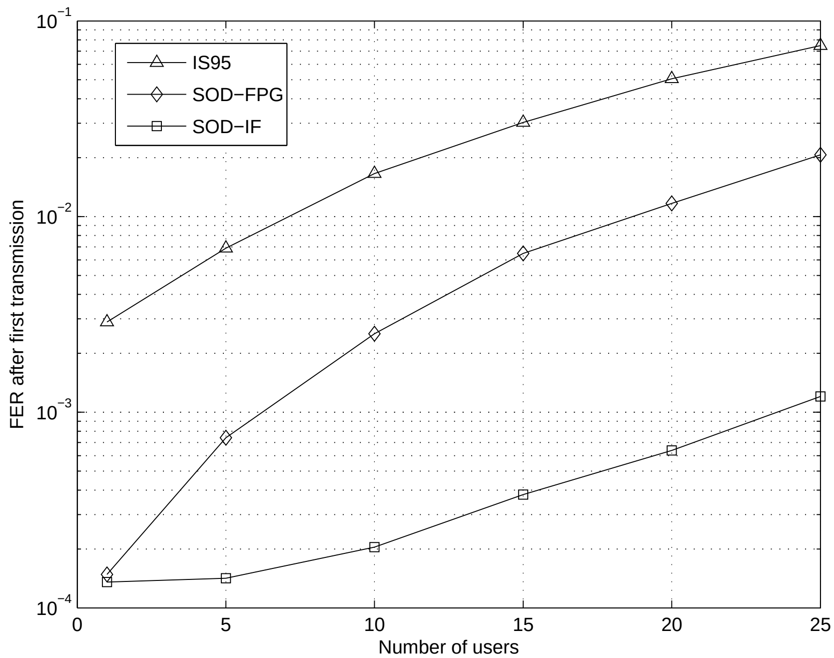

Fig. 8. Coded case with Rayleigh fading.

In Figure 8, FER is plotted versus the number of users K. Three curves are reported. IS95 refers to a system that uses the same parameters as the IS95 system. SOD-FPG refers to a system using the SYCS encoder using the SOD-FPG protocol with $N = 16$. SOD-IF refers to a system using the SYCS encoder using the SOD-IF (Section III-A) with $N = 16$. The curves show the potential of the SOD protocols. For instance, for a targeted FER$= 10^{-2}$, IS95 can support only a number of users $K = 7$, SOD-FPG can support a number of users $K = 19$, and SOD-IF can support a number of users $K \gg 25$. Alternatively, when considering a number of user $K = 10$, IS95 has FER$= 1.6 \times 10^{-2}$, SOD-FPG has FER$= 2.5 \times 10^{-3}$, and SOD-IF has FER$= 2 \times 10^{-4}$.

The initial results for the SOD-IF protocol show the potential gains that can be achieved over traditional IS95 systems. However SOD-IF might present significant technical challenges in a real world implementation. SOD-DF has the potential to provide gains similar to the SOD-IF protocol with a simpler implementation.

VI. Analysis of ARQ-MAC Protocols

The results presented in the previous section are obtained under the saturation throughput assumption and with a constant number of users K, i.e., at each frame, each one of the K users attempts to transmit its frame. In general, in a multimedia or sensor wireless network, users might generate data randomly, e.g., according to a Poisson process. In such a situation, an access protocol is necessary. This section shows some preliminary results and considerations for this case.

This section presents some initial results and consideration on ARQ-MAC protocols. The assumption made is that packet arrival is a random process. For simplicity, the access protocol is chosen to be slotted Aloha (S-Aloha) [44]. With S-Aloha all users must synchronize their transmissions at the beginning of a slot. The number of transmitted frames during a slot is then constant throughout a slot. (Notice that this is not the case with unslotted Aloha.) In this study, S-Aloha is applied to an SS system, i.e., SOD-FPG (Section V) with $N = 16$. The resulting cross-layer access protocol is termed S-Aloha-SOD-FPG. In estimating the throughput, the number of users is assumed to be infinite, packets are generated according to a Poisson process with arrival rate λ, and users attempt transmission in the slot following the packet arrival. Unsuccessfully transmitted packets are discarded. Additionally, it is assumed that all destinations receive the same power level from every transmitting user. Each packet contains 105 data bits. The same CRC and RCPC parameter values indicated in Section V are used here. Let Y be the random variable denoting the number of packet arrivals in each slot. Then:

$$P(Y = y) = \frac{\lambda^y e^\lambda}{y!}. \tag{11}$$

The number of successfully transmitted packets per slot, i.e., the throughput S_y, conditioned to y packet arrivals in the previous slot is

$$S_y = y\left(1 - FER(y)\right). \tag{12}$$

$FER(y)$ is the FER when y users are transmitting in the same slot and the value of $FER(y)$ is derived as indicated in Section V. The throughput is then:

$$S = \sum_{y=1}^{\infty} S_y \frac{\lambda^y e^\lambda}{y!}. \tag{13}$$

For comparison, the plain S-Aloha (without SS) is used. In the plain S-Aloha, the transmission bit rate is set to be equal to the chip rate of the S-Aloha-SOD-FPG protocol. In plain S-Aloha 105 data bits plus CRC, i.e. a total of 120 bits per packet, are transmitted, i.e, no RCPC code is used.

In the plain S-Aloha it is assumed that a collision-free packet is always successfully decoded at the destination, i.e., the channel SNR is infinite. This scenario is an upper bound (U-bound) for the S-Aloha throughput. The throughput for the plain S-Aloha is computed from [44].

Figure 9 shows the throughput S versus the arrival rate λ. Note that the curve for the S-Aloha-SOD-FPG protocol takes into account thermal noise and fading. S-Aloha-SOD-FPG exceeds the throughput of S-Aloha. Interestingly, S-Aloha-SOD-FPG yields maximum throughput at a lower arrival rate compared to plain S-Aloha. Consequently, at maximum throughput, the number of backlogged packets, i.e., packets that need to be retransmitted, is lower in S-Aloha-SOD-FPG when compared to S-Aloha. This suggests that the conventional exponential backoff retransmission technique used in S-Aloha [44] might not be the optimal for S-Aloha-SOD-FPG. However, if retransmissions are too aggressive, i.e., immediately after the unsuccessful transmission, the S-Aloha-SOD-FPG protocol could go into instability, i.e., the throughput goes to zero. When retransmissions are taken into account, and error-free reception is accomplished by means of ARQ, it is expected that the latency in a S-Aloha-SOD-FPG network is much lower than in a network based on S-Aloha.

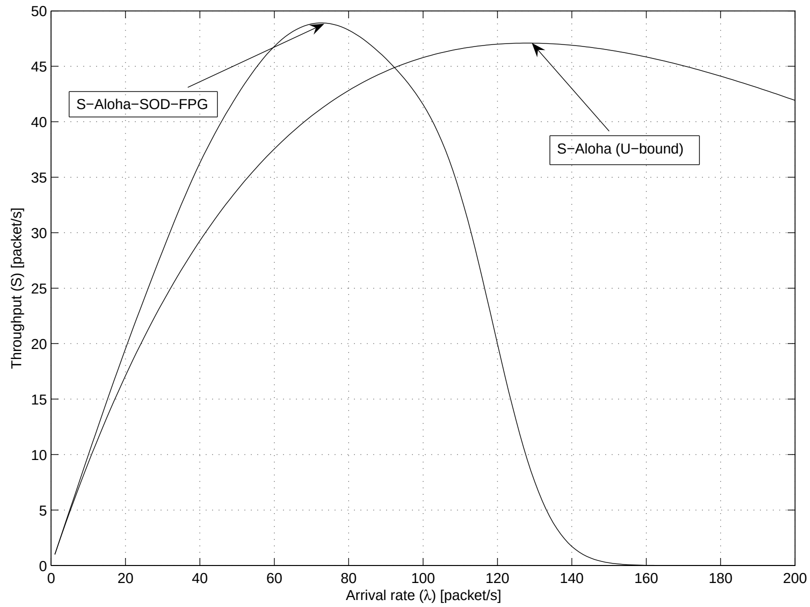

Fig. 9. Throughput of S-Aloha with and without SS.

VII. Research Challenges

The presented results show that by relying on the SOD adaptable processing gain, it may be possible to partially or totally replace today's close-loop mechanisms that control the instantaneous transmitted power level in SS networks. While continuously adapting the processing gain and transmitted frame length to meet the instantaneous channel and symbol interference conditions, the access protocols based on SOD provide a built-in mechanism to control the energy transmitted per frame in real-time, without requiring any change of the instantaneous transmitted power level. SOD adaptable processing gain may then prove to be useful especially when accurate channel prediction is difficult to make. If this technique is demonstrated to be stable, it will offer an appealing built-in and self-adjusting distributed power control mechanism for many wireless networks.

As indicated in Section III, when applying SOD to wireless multimedia networks, several open issues must be addressed.

- Analysis of SOD-MAC. Analysis of SOD-MAC needs to be carried out taking into account several factors, e.g., frame length, code rate and its generator vector, power efficient ACK schemes for SOD-IF, signaling schemes, load in the system, SINR, and performance objectives when combined with FEC in realistic wireless channel conditions.
- Multi-user receivers. The performance of SOD-MAC needs to be investigated when using multi-user receivers that operate with the information of a subset of the active users' signature waveforms (e.g., partial decorrelating receiver [45]). This type of receivers is a practical option when multiple distinct networks coexist in the same radio space, i.e., when it is difficult to know all the active users' signature waveforms.
- Minimize frame detection attempts for SOD-MAC. To implement SOD-MAC efficiently, the receiver must choose $T_d^{(1)}, T_d^{(2)}, \ldots$ efficiently in order to avoid CRC check failures and unnecessary signal processing tasks. This requires to develop quick methods for estimating the instantaneous SINR (or received power) of a SOD-MAC user, for example, by extending the work in [46].
- SOD-MAC with buffering at the receiver. When buffering at the receiver is an option, off line decoding of the received mini-frames can be applied to increase throughput at the price of increased latency

and computational complexity. At decoding attempt $n \leq N$, where N is the number of mini-frames in a frame, there are $2^n - 1$ possible subsets of mini-frames. It is clearly not feasible to try all possible combinations in order to maximize the probability of reliably decoding the frame. A techniques to select the optimal (or near-optimal) subset of mini-frames that maximizes throughput, i.e., the subset of mini-frames that minimizes latency and additional complexity, needs to be studied.

- Unslotted frame transmissions. The effect of unslotted frame transmissions, uneven frame length, correlated and uncorrelated interference in SOD-MAC protocols need to be investigated.
- SOD-MAC with adaptive coding. The integration of SOD-MAC with RCC codes [47] and study its performance to understand the spreading versus coding trade off needs to be analyzed.
- Quality monitoring for real-time applications. Reliable frame error detection is achieved by adding CRC bits. However, real-time applications, such as voice and video, might not employ CRC bits. On the other hand, SOD-MAC protocols require CRC bits to continuously monitor the channel condition and adapt the instantaneous processing gain. The performance trade off and possible penalty that real-time applications may experience when using SOD-MAC protocols needs to be studied.
- Robustness to impairments in the physical layer. SOD-MAC protocols exploit the channel performance gain in the physical layer to improve the overall network performance. The sensitivity of SOD-MAC to physical layer impairments such as channel estimation errors and non-linearity of the high power amplifier needs to be investigated.
- Coarse channel estimation. In SOD-MAC protocols, the receiver can keep track of the history of the number of mini-frames used to correctly decode a frame. Such number can provide a coarse indication of the channel conditions by simply decoding one single user. Techniques are needed to take advantage of this knowledge in order to simplify the network control overhead.
- Cross-layer access protocols based on SOD. Performance models and bound estimators need to be developed to characterize the cross-layer access protocols based on SOD, i.e., throughput, delay, number of retransmission attempts, etc.
- ARQ-MAC retransmission strategies. Alternative options to the conventional exponential backoff algorithms (when dealing with unsuccessful transmission attempts) need to be analyzed. For example, the retransmission strategy can be made adaptive to the channel condition by taking advantage of instantaneous SINR measurements.
- ARQ-MAC for SOD-DF adaptive mini-frame control. With SOD-DF, the ARQ-MAC protocol must provide a feedback to the transmitter on the maximum number of mini-frames to be used in the next transmission attempt.
- Support for multimedia and datagram traffic. The cross-layer access protocols based on SOD must be able to differentiate users' generated traffic into multimedia classes, e.g., real time and datagram. Differentiation can be provided at either sub-layers, i.e., in the SOD-MAC by varying the processing gain, and in the ARQ-MAC by varying the backoff algorithms.
- Support for QoS. Multiple classes of services, e.g., UGS, RTPS, NRTPS like classes, needs to be considered as opposed to having only just one for real-time and one for datagram.

VIII. Conclusions

The objective of this report is to propose cross-layer medium access control (MAC) protocols based on SOD. The uniqueness of these cross-layer access protocols is their ability to combine two features to maximize the radio channel utilization, i.e., statistical multiplexing of traffic generated by an unbounded number of uncoordinated wireless nodes and JER in the transmitted frames. Additional advantages deriving from these protocols include contained network latency, energy efficient transmission/reception operation at the wireless node, and a QoS platform for both real-time and datagram traffic.

By addressing two families of cross-layer protocols, the report offers two alternatives to harness the adaptable processing gain of SOD. The first (SOD-IF) is a high risk, high reward approach to accomplishing JER with instantaneous feedback, based on full duplex channel capability and fast decoding algorithms. The second (SOD-DF) represents a lower risk solution from the hardware viewpoint, which requires smarter access protocols to retain most of the JER offered advantages by means of delayed feedback.

If these cross-layer access protocols are successfully designed and demonstrated, they may be applicable to a variety of wireless network solutions, including WLANs and wireless sensor networks. In which case, they are expected to complement currently existing protocols (see Section IV for a survey) especially in wireless node-crowded areas. They may provide a versatile QoS platform to higher layers, thus, spinning off a number of additional research efforts, e.g., routing solutions in ad hoc networks and end-to-end flow control solutions specifically designed to take advantage of the unique SOD features.

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