Power-Congestion-Distortion Optimized Transmission for Wireless Multimedia Sensor Networks

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Abstract Wireless Multimedia Sensor Networks (WMSN) brings a new set of design challenges due to their specific application requirement, stringent delay, complexity and power constraints. To meet the particular demands of efficient communication in WMSN, a cross-layer design (CLD) approach is proposed in this paper. We make use of off-the-shelf algorithms with a specific emphasis on physical and transport layers, while exploiting the information exchanged between the layers. An application layer power-congestion-distortion (P-C-D) optimized transmission policy was proposed for multi-path and real-time multimedia communication. Simulation results showed optimal trade-offs can be made between available routes and transmission opportunities such that communication power is minimized under an end-to-end distortion constraint.

1 Introduction

Sensor networks, and in particular wireless sensor networks (WSN) have attracted a lot of attention in the recent years. The ability of being dispatched in large numbers, effectively collect and communicate information make them suitable for a wide array of applications. Many proposed or existing algorithms and protocols are for sensor nodes taking simple measurements such as temperature and humidity, tracking of target movements or inventory. The deployment of Wireless Multimedia Sensor Networks (WMSN), on the other hand, calls for another set of application requirements which must be carefully considered [1,2]. Multimedia applications are typically delay constrained, have large bandwidth requirement, produce bursty bit streams and are somewhat loss tolerant. They generally require higher level of computational complexity (and power) compare to the other applications. At the same time, the tight delay constraint, burstiness of traffic and loss prone wireless links make the network management problem more challenging. In addition, these new constraints must be dealt with in a energy efficient manner as in other wireless sensor networks. Various algorithms and protocols can be applied to the different OSI layers to limit power consumption. Extensive reviews of these approaches can be found in [3,4].

Meanwhile, to ensure reliable multimedia communications in wireless networks, the cross-layer design (CLD) paradigm has gained vast popularity. It is believed that through joint operation and optimization of the OSI layers, better performance, less complexity and application specific quality of service can be achieved [5]. Some CLD techniques are specifically for cellular networks or single wireless links, [5],[6]. WMSN on the other hand is more closely related to the ad hoc network setting where the network generally has no pre-defined structure and is self-configured [7]. For example, techniques such as Congestion Distortion Optimization (CoDiO) for either scheduling or multi-path routing [9] take both the queuing delay in the ad hoc network and distortion constraint from the application into consideration in the optimization process. However, only rather simplified M/M/1 type network model was used and issues such as power efficiency was not addressed. Nevertheless, these approaches demonstrate the influence and importance of transport and network layer protocols in the network. A cross-layer power control scheme was proposed in [10]. Here existing transport layer protocol such as TCP-Vegas was jointly optimized with power control to regulate the capacity on the wireless multihop link. Although implicitly contained in the link capacity-power relation, no explicit physical (PHY) layer parameters were included in the optimization. Neither was application layer requirement any part of the equation. In the recent work of [11], a power allocation scheme was proposed for wireless video sensor network based on an analytical power-rate-distortion model. Little consideration however, was given to the sensors operating as a network.

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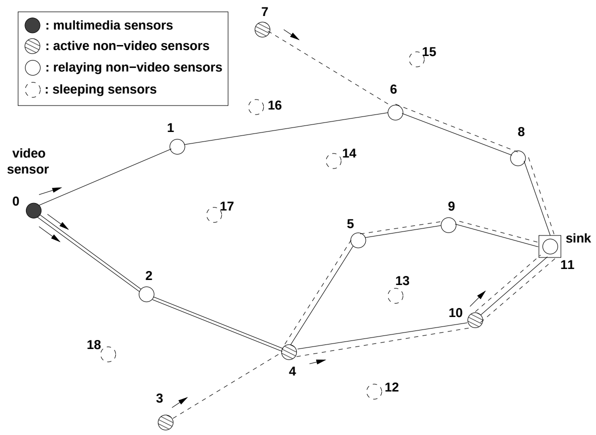

Fig. 1 WMSN topology

In this paper, we propose a novel power-congestion-distortion optimized transmission scheme for WMSN using the cross-layer design approach. We emphasize that since resources are scarce in a WMSN, every piece of information captured is useful information. That is, from a sensor node point of view, any encoded source bits should be transmitted, received and decodable by the sink. This imposes the following requirement: 1. packets should not be dropped during transmission due to network congestion. 2. packets should arrive at the receiver on time so they will not be discarded due to the strict decoding deadline and 3. the packets should not contain so many bit-errors such that they are not decodable. The main contribution of our work is to apply the cross-layer design approach on existing transport, medium access (MAC) and PHY layer protocols and algorithms under these criterions, while at the same time making sure the WMSN application requirement is met.

2 Power Efficient Transmission over WMSN

Inherently all ad hoc networks including WSNs and WMSNs have time-varying topologies and yet equipped with routing protocols to handle these variations. In Figure 1 we consider a random snapshot of a time-varying WMSN topology which can be defined by the set of sensing nodes (or motes) $\mathcal{M}$, active links $\mathcal{L}$ and source-to-sink routes $\mathcal{R}_m$, $\forall m \in \mathcal{M}$. We use "link" to describe the wireless channel between two nodes and "path" or "route" for the sender-to-sink connection. Furthermore each available route $r \in \mathcal{R}_m$ for sensing mote m is described by a set of active links $\mathcal{L}_r$ *sorted* in a source-to-sink fashion and defined over $\mathcal{L}$. Upon the multimedia sensor mote m is activated by an event, it samples the input multimedia signal at frequency f, encodes at rate R_T bit per source slice s and transmits over a set of routes $\mathcal{R}_m$ to reach the receiver node (sink) m_r throughout an event duration which is called as a "session". Note here that we consider explicitly a multi-path, multi-hop transmission scenario. We focus on wireless channels with relatively slow time varying channel condition, for example a Rayleigh flat-fading channel. That is to say that the channel conditions are assumed to be static for the duration of transmitting one packet, from one node to another.

In a WMSN, the main purpose of the application is, generally speaking, not to obtain the best quality of the decoded multimedia source. Instead, it is more important to maximize the lifetime of the network while maintaining a desired level of quality. Such quality constraint can be translated into having fixed level of allowed end-to-end distortion. For the moment we limit our attention to minimizing transmission power consumption, that is, energy consumed for transmitting a number of packets over a time period. For the rest of the paper, we refer to transmission power as simply power unless stated otherwise. We therefore have the following task at hand: given the WMSN communication session of S slices, what is the optimal policy to allocate and encode bits from the sender node to the *different* paths, such that the total transmission power consumed by all nodes involved are minimized, while the total average end-to-end distortion is below a threshold D_c:

$$\begin{aligned} \min_{\pi(s)} \quad & \sum_{s=1}^{S} P(\pi(s)) \qquad (1) \\ \text{s. t.} \quad & E\{D_{tot}(\pi(s), R_T)\} \leq D_c \ , \end{aligned}$$

where under policy $\pi(s)$, $P(\pi(s))$ is the end-to-end power consumption and $D_{tot}(\pi(s), R_T)$ is the distortion due to compression error and packet losses for slice s.

In the following sections, we describe in detail the functions of the OSI layers, the necessary assumptions and the optimization frame work.

2.1 Physical Layer

The main responsibility of the PHY layer in a wireless network is to modulate and transmit the signal at a certain power level. In [12], Yoo et al proposed an optimization framework for maximizing the system throughput of a wireless link, which is defined as the number of correctly received payload bits per second. They concluded that by optimally adapting the PHY layer parameters such as symbol rate R_s, constellation size b, and packet size L, a constant gap can be achieved from the Shannon capacity, regardless of the received SNR. In other words, the optimal symbol SNR γ^* can be obtained by first observing the current symbol SNR γ of the wireless channel, followed by adaptation of the PHY layer parameters. The remaining bit errors can be corrected by applying Forward Error Correction (FEC) codes such that the packet success rate can then be made to nearly 100%. The adaptive PHY layer techniques can greatly alleviate the burden for the upper layers when dealing with varying wireless channels. This essentially meets the requirement 3 for WMSNs we stated in the introduction.

Due to the limited complexity and processing power in a WMSN, we consider parameters such as constellation size b and packet size and L of radio transceivers to be fixed for the session. This inherently restricts system throughput maximization when the channel SNR is high [12]. On the other hand in medium or low SNR region for $\gamma \leq \gamma^*$ maximum system throughput is achievable by symbol rate adaptation. It was noted that varying R_s is not easy to implement in practice [12],[13]. We therefore set $R_s = W$, where W is the transmission bandwidth, and resort to the technique of power adjustment in Time Division Multiplexing Access (TDMA) to obtain an equivalent symbol rate variation. Given a fixed average power budget P_{avg}, for a packet length L and b bits per symbol, there are $L_s = L/b$ symbols for each packet. For a MAC layer frame with length $L_f \geq L_s$, by activating transmitter only in a portion of L_f and adjusting the power level at the same time to L_f/L_s times higher, we reach the desired SNR level $\gamma^* = \frac{(L_f/L_s)P_{avg}}{N_0 R_s}$, where N_0 is the noise spectral density. The power adjustment ratio is then $\frac{L_f}{L_s} = \frac{\gamma^*}{\gamma}$, for $\gamma > 0$. Note that in this regime, inter packet time is varying due to the changing L_f. However, packet transmission time τ_p is kept constant and is determined by $\tau_p = L/(R_s b)$.

The optimal transmission policy requires knowledge of future channel states for proper provisioning of packets on the active routes. This information can be obtained using a finite state Markov chain (FSMC) model of the channel. We assume that channel state variation only occurs between adjacent states and the channel can be perceived as AWGN for the duration of a packet transmission τ_p. For a given current time t_n we define the observed SNR of link l at a future time $t_k \geq t_n$ as $\gamma_{n,l}^{(k)}$. The corresponding link capacity $c_{n,l}^{(k)}$ is calculated as in Eqn. 2, where $\delta \in [0,1]$ denotes the overhead ratio due to MAC packet header, CRC and FEC[1].

$$c_{n,l}^{(k)} = \begin{cases} (1-\delta)bR_s \frac{\gamma_{n,l}^{(k)}}{\gamma_l^*} & \text{, for } \frac{\gamma_{n,l}^{(k)}}{\gamma_l^*} \leq 1 \\ (1-\delta)bR_s & \text{, for } \frac{\gamma_{n,l}^{(k)}}{\gamma_l^*} > 1 \end{cases} \quad (2)$$

For a given current time t_n, power consumption estimate $P_{n,l}^{(k)}$ at $t_k \geq t_n$ on link l is calculated as [8].

$$P_{n,l}^{(k)} = \begin{cases} P_{avg}(1-\delta)bR_s/c_{n,l}^{(k)} & \text{, for } \gamma_{n,l}^{(k)} > 0 \\ 0 & \text{, for } \gamma_{n,l}^{(k)} = 0 \end{cases} \quad (3)$$

The FSMC model partitions the whole SNR range and maps it onto a state space $\mathcal{X} = \{0, 1, ..., N\}$ with finite dimension $N+1$. We define the transition probabilities denoted by the state transition matrix $\mathbf{P}_l$. The SNR levels corresponding to a state $x \in \mathcal{X}$ is defined by the function $\mathit{\Gamma}_l(x)$. The state vector $\bar{a}_{n,l} = [a_{n,l}(0)...a_{n,l}(N)]$ defines the probability of being in each state at time t_n. Given the above definitions and properties of Markov chains, the channel state $\gamma_{n,l}^{(k)}$ at time t_k is calculated as follows for a given current state $\bar{a}_{n,l}$ at time t_n:

$$\begin{aligned} \bar{a}_{k,l} &= \bar{a}_{n,l}\mathbf{P}_l^{\lceil (t_k - t_n)/\tau_p \rceil} \\ \gamma_{n,l}^{(k)} &= \mathit{\Gamma}_l(\arg\max_{x \in \mathcal{X}}(a_{k,l}(x))) \end{aligned} \quad (4)$$

2.2 MAC Layer and Network Layer

The MAC layer controls how the common wireless medium is shared amongst users. As pointed out in [2], power saving using contention based protocols often leads to higher latency, lower throughput and abrupt change of quality in playback. We therefore consider a contention-free MAC layer protocol which transmission is guaranteed for the designated time slot. The synchronized access schedule can be maintained by the sink node. Power increase for such inter-cluster multi-hop communication may result in reduced access opportunity for neighbouring clusters but is compensated by adaptive link techniques described earlier. Since symbol rate is adjusted by varying the MAC layer frame size L_f, other users will get the opportunity to access the channel.

We do not consider a specific network layer protocol in our optimization framework. The basic requirement is that a set of routes are determined by the protocol at the beginning of the transmission session and they should be active through out the session. The routing metrics can be based on a set of parameters such as power, delay and quality of service requirement from different traffic classes.

2.3 Transport Layer

The transport protocol plays an essential role in regulating traffic flows of the network. It ensures fairness between flows and performs congestion control. Loss based congestion control schemes suffer from the well known ambiguity between packet losses due

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[1] Due to the delay sensitive nature of multimedia applications, we do not consider error control scheme such as ARQ (automatic repeat request) on the data link layer.

to congestion and wireless link errors. In addition, packet losses put extra burden on upper layers for implementation of error correction algorithms. More importantly, as we described earlier in requirement 1 in introduction, each packet drop signifies a major waste of *processing* and *communication power* that had already been spent on the encoding and prior relaying nodes.

A class of accumulation based congestion avoidance protocols such as TCP-Vegas, on the other hand, has the ability of anticipating onset congestion and subsequently avoiding it. By applying such transport protocol, combined with the optimal transmission policy, requirement 1 stated in the introduction can be met.

In TCP-Vegas, the source monitors the difference between its expected rate and the actual sending rate and adjust its transmission window accordingly To determine this rate difference, the source m estimates the round-trip *propagation* delay $d_r = \sum_{l \in \mathcal{L}_r} d_{r,l}$ on route $r \in \mathcal{R}_m$ as the sum of individual link propagation delays $d_{r,l}$ and adjust its rate, based on the additional *accumulation* α_r experienced in the network queues (i.e. *queueing delay*). At current time t_n, the transport layer of mote m estimates the throughput $x_n^{(k)}(r)$ and average end-to-end delay $D_n^{(k)}(r)$ at time $t_k = t_n$ for route $r \in \mathcal{R}_m$. In addition, the future estimates at time $t_k > t_n$, provided by the sink, will be used in constructing the optimal transmission policy. The allowed throughput at current time t_n on each route can be obtained by maximizing the logarithmic utility function of TCP-Vegas in a distributed manner , as shown in [10]:

$$\begin{aligned} \max_{x_n^{(k)}(r)} & \sum_{m \in \mathcal{M}} \sum_{r \in \mathcal{R}_m} \alpha_r d_r \log x_n^{(k)}(r) \qquad (5) \\ \text{s. t.} & \sum_{m \in \mathcal{M}} \sum_{\substack{\forall r \in \mathcal{R}_m: \\ l \in \mathcal{L}_r}} x_n^{(k)}(r) \le c_{n,l}^{(k)} \ , \ \forall l \in \mathcal{L}_r \end{aligned}$$

where channel capacities $c_{n,l}^{(k)}$ are the maximized system throughput from Section 2.1.

Using a fixed α_r and assuming a uniform distribution of accumulation α_r over congested links, the mean end-to-end delay $D_n^k(r)$ at time t_k is:

$$\begin{aligned} q_{n,l}^{(k)} &= \sum_{m \in \mathcal{M}} \sum_{r \in \mathcal{R}_m} \alpha_l(r)/c_{n,l}^{(k)}, \text{ for } l \in \mathcal{C}_r \\ D_n^{(k)}(r) &= d_r + \sum_{l \in \mathcal{C}_r} q_{n,l}^{(k)} \qquad (6) \end{aligned}$$

where $\mathcal{C}_r$ is the set of congested links with cardinality C_r, $\alpha_l(r) = \alpha_r / C_r$ is the number of accumulated packets on link l of route r.

2.4 Application Layer

In the application layer we propose a P-C-D (Power-Congestion-Distortion) optimized multi-path packet transmission policy for WMSNs, based on the concept of CLD. The main goal of the P-C-D algorithm is to fulfill the requirement 2 stated earlier in the introduction, while minimizing power consumption. Details of the proposed P-C-D optimization algorithm will be provided in the following sections.

3 Power-Congestion-Distortion Optimization

Ideally, the optimization problem stated in Eqn. 1 requires the prior knowledge of distortion information per slice and transmission opportunities that will appear throughout the session. However, in order to operate in real time, we limit the time horizon of future information to the (input) buffer, and apply the optimization as we proceed in time. At a given optimization instant t_n, the P-C-D optimized policies $\pi_n(s) = (t_n(s), r_n(s))$ select the optimum route $r_n(s)$ and transmission time $t_n(s)$ for each slice s in the transmission buffer. $\{s_n, ..., S_n\}$ represents the slices in the transmission buffer at time t_n where s_n and S_n denotes the slice at the head and end of the buffer respectively. Then in order to simplify the notation we define two functions $r_n(s) = R(\pi_n(s))$ and $t_n(s) = T(\pi_n(s))$ which respectively returns the selected route and transmission time for a given policy. Finally we define the total distortion term for a slice s under policy $\pi_n(s)$ and coding rate R_T as the sum of coding distortion D_e and packet loss distortion D_v as $D_{tot}(s, R_T, \pi_n(s)) = D_e(s, R_T) + D_v(s, R_T, \pi_n(s))$. The D_v term relates distortion to the mean end-to-end delay estimate $D_n^{(k)}(r)$ at time t_k. Hence we can convert the problem in Eqn. 1 into the following form Eqn. 7 by only considering the slices $[s_n, S_n]$ in the transmission buffer.

$$\begin{aligned} \min_{\pi_n(s)} & \left\{ \sum_{s=s_n}^{S_n} \sum_{\substack{l \in \mathcal{L}_r \text{ for} \\ r = R(\pi_n(s))}} P_{n,l}^{(g(T(\pi_n(s)),R(\pi_n(s)),l))} \right\} \qquad (7) \\ \text{s. t.} & \ \frac{1}{S_n - s_n + 1} \sum_{s=s_n}^{S_n} D_{tot}(s, R_T, \pi_n(s)) \le D_c \end{aligned}$$

In Eqn 7, power consumption estimation $P_{n,l}^{(k)}$ on link l is computed at time $t_k = t_{g(T(\pi_n(s)),R(\pi_n(s)),l))}$ by Eqn. 3. Estimation time $t_{g(\tau,r,l)} = t_{g(T(\pi_n(s)),R(\pi_n(s)),l)}$ is recursively calculated as in Eqn. 8. Hence, the estimated power consumption on link l is determined by slice policy $\pi_n(s)$ and queueing plus propagation time spent in the network until reaching the link l. In the expression for $t_{g(\tau,r,l)}$, $d_{r,l}$ is given as the

PHY/MAC	Transport	Application
$L = 4096$bits $W = 125$MHz	$d_{r,l} = 1$ msec	$f = 3$ frames/sec
$f_c = 2.4$GHz $b = 2$ bits/symbol	$\alpha_r = L$ bits/flow	Quant.Par. = 32 (H.264 encoder)

Table 1 Simulation parameters of different OSI layers

propagation delay of link l and $\mathcal{A}_r(l)$ returns the predecessor (ancestor) of link l within the source-to-sink route r.

$$t_{g(\tau,r,l)} = \begin{cases} \tau & , \mathcal{A}_r(l) \text{ not valid} \\ t_{g(\tau,r,\mathcal{A}_r(l))} + q_{n,l}^{(g(\tau,r,\mathcal{A}_r(l)))} + d_{r,\mathcal{A}_r(l)} & , \text{o.w.} \end{cases} \tag{8}$$

Multimedia node m estimates the possible transmission opportunities within a horizon of $[t_n, t_n + T_p]$ on each route $r \in \mathcal{R}_m$. In Eqn. 9 the recursive function for the calculation of transmission opportunities $t_k(r) \in [t_n, t_n + T_p]$ on route is given where $\hat{t}_n(r)$ denotes the last (passed) transmission opportunity on route r known at time t_n.

$$t_k(r) = \begin{cases} \hat{t}_n(r) & , \text{ for } k = n \\ t_{k-1}(r) + \frac{L}{x_n^{(k-1)}(r)} & , \text{ othewise} \end{cases} \tag{9}$$

Hence, knowing these opportunities, multimedia node m can solve the constrained optimization problem in Eqn. 7 by using lagrange multipliers for the equality condition in constraint. At this point we can define the transmission window policy matrix at t_n as $\mathbf{\Pi}_n = [\pi_{s_n}(n) ... \pi_{S_n}(n)]$. Then P-C-D optimization algorithm applies multivariate minimization to find the optimal $\mathbf{\Pi}_n^*$ that minimizes the lagrangian cost function in Eqn. 10

$$J(\mathbf{\Pi}_n) = P(\mathbf{\Pi}_n) + \lambda(D_{avg}(\mathbf{\Pi}_n) - D_c), \tag{10}$$

where $P(\mathbf{\Pi}_n)$ and $D_{avg}(\mathbf{\Pi}_n)$ are respectively the objective function in curly brackets and the left hand side term of the constraint in Eqn. 7.

4 Simulation and Discussion

The proposed optimization frame work was simulated using parameters given in Table 4. We present the main results in Figure 2. The packet loss distortion D_v versus the power consumed per packet P is plotted for various Lagrange multiplier λ, as in Equation 10. Same number of packets were transmitted over fast and slow Rayleigh fading channels with a maximum Doppler frequency of $f_m = 0.5555$ Hz and $f_m = 2.2222$ Hz. In both fast and slow fading, we observe a waterfall like relation between D_v and P in *joules/sec/packet* (j/s/pkt) over a range of λs. When the λ value is small, the transmission policy takes little of the distortion constraint into account. The sender may have to wait longer for a "better" route condition that results in lower power consumption. This additional delay may cause the packet to miss its decoding deadline. In addition, when the sending buffer is full due to the excess waiting time, sensing will have to be temporarily stopped which again results in additional end-to-end distortion. When λ is zero, the least power consuming policy is clearly to stop transmission. Note the distortion level is relatively flat and at its maximum when P is below 6 j/s/pkt. As λ increases, the optimized transmission policy becomes more affective and D_v drops drastically over a short power increment.

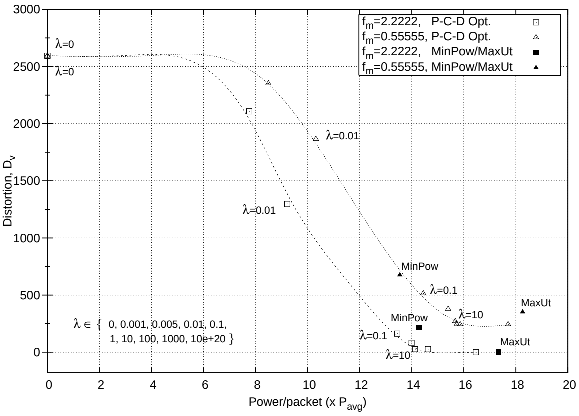

Fig. 2 Power-distortion trade-off under fast-slow fading

When λ is greater than 10 and power exceeds 14 j/s/pkt, we reach the bottom of the waterfall, where all packets are able to arrive on time in the fast fading case and D_v remains at the minimum level of 250. This is no surprise since in a fast fading environment, the routes conditions vary quickly and the optimal transmission policy is able to exploit all the possible transmission opportunities to meet the decoding deadline. In a slow fading case, however, the routes may remain in a bad channel state long enough that certain packets can no longer meet their deadline.

We also investigated the two boarder cases, namely, the minimum power (MinPow) and maximum utilization (MaxUt) policies, where the transmission schedules are constructed heuristically and no optimization is performed. With the minimum power policy, amongst the available routes, the one has the least transmission power is always chosen. The transmission opportunities are not as frequent as when the higher power consuming routes are also used. Packets that are not going to meet their decoding deadlines will have to be dropped at the sender. We then have a relative "conservative" transmission scheme. On the other hand, if power can be consumed generously, the sender will aggressively send all available packets at *all* available transmission opportunities on *all* active routes to minimize the distortion due to delay. The maximum utilization policy subsequently consumes the most power, as shown in Figure 2. Note the minimum power policy, although no optimal, results in a relatively low distortion level. This is due to the fact that by *not* looking into the future when provisioning the available bandwidth, the sender secures the transmission opportunities on the least power consuming route such that at least *some* packets are always transmitted and meet their deadlines.

The simulation results indicate that in both fast and slow fading environment, the optimal transmission policy demonstrates most of its strength when the λ is chosen large. Meanwhile, the heuristic approaches can provide reasonable performance with much lower complexity. Especially in the case of the maximum utilization policy, the additional power consumption is limited compare to the P-C-D optimized scheme. This property makes it attractive when the power levels are supported by the relay nodes in the WMSN.

5 Conclusions and Future Work

Energy efficient reliable transmission in a multi-path, multi-hop WMSN can be achieved through a combined effort of the OSI layers. Based on the strict application requirement, we proposed a power-congestion-distortion optimized transmission policy that utilizes the existing OSI layer algorithms and protocols. By intelligently schedules the packets on the available routes at the suitable transmission opportunity, the probability that a packet misses its decoding deadline is minimized. Congestion is avoided with a transport protocol using accumulation based congestion control, combined with optimal packet scheduling. While maintaining a average end-to-end distortion level, the over all transmission power consumed is minimized by choosing the proper route for each packet. Our simulation results show that in both fast and slow fading wireless channels, with a large λ value, the proposed scheme is able to achieve minimum distortion due to late arriving packets, while minimizing the power-distortion cost function. We also examined the two heuristic transmission policies which either take only power or only distortion due to delay into account. These simple approaches are also show to be quite affective.

While WMSN is generally highly application specific, multimedia transmission over a generic wireless ad hoc network may introduce additional design parameters. Consider a wireless ad hoc network that is formed by a collection mobile terminals, laptops and other hand held devices. The multimedia traffic may be co-existing with data transfer and traffic flows may no longer be uni-directional. In addition, the network topology information may be less likely available to the sender to assess the queuing delays on the relay nodes. Nevertheless, the basic principles behind our proposed scheme here can be extended to the general wireless ad hoc network setting, while taking the corresponding network and transport layer issues into account. A more network aware application layer algorithms can also be incorporated.

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