Adaptive epidemic dissemination in wireless ad hoc networks

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Abstract. The focus of this research is adaptive epidemic dissemination (AED) of information in wireless *ad hoc* networks. The main targets are the tradeoff between demands for broad information dissemination and reduced energy cost, the putsuit of an optimal solution to the problem and also the achievement of optimal performance in the aforementioned areas with high quality information.

Feedback-based AED schemes can be engineered that exploit context awareness in the form of channel state information (CSI) [1]

Besides such reactive and feedback-based schemes, others of a more proactive flavor can also be devised that use utility functions in order to adapt transmission characteristics according to predicted benefit [2]. With this approach a broad variety of benefit metrics can be exploited.

Introducing optimal stopping (OS) in the adaptation of transmission characteristics allows for visibility longer into the future and an optimal solution approach. The use of the one-stage-look-ahead, (*1sla*) OS rule displays improvement over non-adaptive schemes in terms of energy cost save while broad network infection remains as effective [3].

Optimization is further investigated in the broadcast scheduling problem, which is addressed with a transition to a *near-periodic* framework. According to this, scheduling is performed using the same toolcase of cross-layer utility functions and an optimal stopping mechanism. This problem is modeled as a *classical secretary problem* where the use of OS offers optimality. Compared against non-OS [2] and non-adaptive schemes this scheme wins in the energy cost save area and allows for successful network infection. In this case, the system converges to a state where dissemination cost is dramatically reduced while a large proportion of the residual, steady-state energy cost is due to CSI acquisition [4].

Furthermore, the possibility to improve information quality is investigated with information freshness originally assumed as the measure of quality. Adaptation of transmission characteristics based on information freshness is suggested aiming to lower the average age of the infecting information. In this manner, the idea of adapting transmission characteristics based on the actual payload of the infecting information is introduced.

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Tuning broadcasts down to a *polite gossip* during the route discovery phase in routing protocols for ad hoc networks is an additional attractive area. This problem is addressed within the framework of the AODV protocol. The tradeoff between energy cost save and fast routing information discovery emerges here. In an attempt to expand the technique to the actual routed data transmission (i.e. the user data), we move from broadcasting to a unicast landscape. Here, the tuning down of transmissions may have significant impact on information propagation. It is shown that the problem is best addressed using metrics reflecting a conceived quality of service and by extension quality of information.
The transmission scheduling problem enhanced by the additional information quality requirement can be formally expressed as an optimal stopping problem with known finite horizon. The quality of the information may be defined based on its properties (such as information freshness) or parameters of the protocol concerned with the dissemination, such as TTL in case of AODV. In this manner, information quality emerges as a third component besides energy cost and network infection, which participates the addressed tradeoff. Depending on the defined information quality the pursuit of a compromise between these three requirements is possible.

Keywords: Ad hoc networks · Adaptive epidemic dissemination · Cross-layer design · Optimal stopping.

1 The Problem Landscape

Epidemic dissemination (ED) [5], [6] aims to deliver broad infection of a network with some specified information while avoiding unconditional transmissions [7]. It is known that the latter cause problems, such as excessive energy cost and communication channel congestion without a corresponding benefit [8].

The performance of ED can be further improved with the introduction of adaptability of the transmission characteristics of the participating nodes. Hence adaptive epidemic dissemination (AED) is brought about [9], [10], [11], [12].

Previous research has delivered several AED schemes [13], [14], most of which are based on feedback mechanisms which exploit context awareness. Both context awareness and transmission characteristics adaptation concern several different network layers at the same time, thus rendering AED a technique of intrinsic cross-layer nature [15]. Adaptation decisions dictated by an AED scheme are taken in a decentralized, distributed manner rather than by a central and hierarchically superior node with full network awareness.

This research attempts to approach an optimal tradeoff among competing requirements in an AED environment and also deliver a strict formalization of this problem. The use of optimal stopping (OS) mechanisms is of central importance in our effort to reach optimality. The application of the technique in transmission scheduling is investigated and envisaged as future research field especially with an emphasis in ad hoc network routing protocols [16].

Let us consider a wireless ad hoc network where it is desired that a single information message be disseminated which is originally resident only in a small percentage of nodes. The latter, according to the established AED terminology are considered *infected*. Obviously, it is desired that the rest of the nodes (the *susceptible* ones) also become infected.

To this end every infected node periodically performs epidemic transmission of the infecting data, i.e. it *attempts* to transmit it: It performs a random experiment with success probability β. If the outcome is successful, then the node will broadcast in an attempt to infect its susceptible neighbors. Therefore, it has finite probability β (forwarding probability) to transmit within a predefined interval.

If the outcome of the experiment is successful and it indeed transmits, it does so using an adaptive modulation and coding (AMC) scheme. The AMC mode is described by the modulation type (e.g. QAM, QPSK, etc) and error-control coding. An important feature of the latter is the coding rate. A specific AMC mode μ shall be used for each transmission.

An infected node may for various reasons lose the infecting information, and then fall back to the susceptible state and be once again ready for new infection. This random process is modelled by a *cure probability*.

In AED models the following are important parameters:

- n: Network node count
- f: The *fan-out*, that is the nodes count targeted by a transmission.
- t: The time interval for which an infected node transmits. This can vary from 0 (*infect-and-die*) to ∞ (*infect-for-ever*).
- b: The node buffer capacity. If the infecting information consists of more than one messages, then this capacity introduces limitations and a mechanism to manage it is required.
- *partial view*: The network overview of an individual node. Essentially it is the count of nodes known to it.

2 Steps Towards the Solution

2.1 Epidemic Dissemination with Cross-Layer Context Awareness

The starting point of the present study is the feedback-based approach which is already familiar from previous research. The context awareness for each node consists of the following information:

- The signal-to-noise ratio (SNR). This knowledge constitutes channel state information (CSI) awareness.
- The proportion of received messages destroyed due to signal degradation while in transit in the channel (channel noise, multi-pathing, etc)
- The number of duplicates received. An infecting message received is considered a duplicate when received by an already infected node.

Exploiting such information awareness, each infected node adapts its AMC mode μ and forwarding probability β according to equations of the form shown in (1).

$$\begin{aligned} \beta(t+1) &= f(\beta(t), \text{context information}) \\ \mu(t+1) &= f(\mu(t), \text{context information}) \end{aligned} \tag{1}$$

Essentially the adaptation of β influences the outcome of the random experiment that the infected node performs when it is about to transmit. Decrementing the β means that the probability of successful outcome (=decision to transmit) is degraded, hence it is less possible for the node to transmit. Adaptation of the β, hence, implies decrease or increase of the number of transmissions and therefore the energy cost. Adaptation of the μ means decrease or increase of the probability of successful reception but also of the associated energy cost due to the respectively varying coding rates. The suitable simultaneous modification of μ takes care that, although reduced in number, transmissions are more likely to result in infections.

The following silent assumptions have been so far made:

- The fan-out equals the number of immediate (single-hop) neighbors of each node. It is essentially defined by the wireless transmitter range.
- The infect-for-ever epidemic model is followed, that is the infected nodes transmit indefinitely unless cured.
- The buffer size is adequate for the storage of an infecting message. This suffices to render the node infected. Saving two copies of the same message is meaningless and hence there is no need of storage space management.
- The node is aware only of the nodes it has received infecting information from

Simulations show that the adoption of the proposed scheme delivers considerably slower energy cost accumulation and also comparable to earlier heuristic AED schemes.

An interesting feature is the avoidance of the energy-intensive dialogues among nodes that cater for context information acquisition. This is a fully passive AED scheme. The overall novelty lies in the departure from heuristic schemes, the combined adoption of cross-layer context awareness, AMC with convolutional coding and immediate adaptation of the forwarding probability.

2.2 Epidemic Dissemination with Prediction: Utility Function with Simple Comparison (*beauty contest*)

A radical departure from the feedback-based approach is brought about by a new scheme that is based on benefit prediction.

It is from now on assumed that *the state of a node* at (discrete) time instance t is exactly described by the pair (β, μ). Therefore, the random experiment with success probability β described earlier is termed *transmitting from state* (β, μ)

Also, from now on, the forwarding probability is discretized to allow for a simplified model and calculations.

Moreover, the wireless channel is described as a finite state Markov channel (FSMC). Each state of the introduced FSMC is mapped to an SNR value range. Hence, the SNR value range corresponding to an AMC mode is mapped to an FSMC state.

Each time instance t the infected node evaluates which adaptation of its state is the optimal. The adaptation is achieved through performing an *action* out of a set of allowed ones presented in Table 1. The choice between increase and decrease of β and μ is based on context awareness and is presented in Table 2.

Table 1. Candidate actions

Action	Adaptation of β	Adaptation of μ
α_1	adapt	keep
α_2	keep	adapt
α_3	adapt	adapt
α_4	keep	keep

Table 2. Exploiting context awareness to decide decrease or increase of β and μ

Context	Actions
SNR increase	decrement β, increment μ
SNR decrease	increment β, decrement μ

The evaluation as to which action is the optimal is done based on the highest predicted immediate utility. This is calculated with the help of a suitable utility function.

This process of transitions can also be modelled with the use of a Markov chain. Each state of the Markov chain is mapped to a state (β, μ) of the node. Figure 1 depicts this approach.

The calculations also show that energy cost save and strong network infection are simultaneously achievable (figure 2).

Figure 2 displays the fact that infection is faster (shorter time-to-full-coverage *T2FC* and shorter time-to-90%-coverage *T29C*) and less energy intensive (lower energy-to-full-coverage *E2FC* and energyto-90%-coverage *E29C*) for adaptive schemes with various utility functions compared to the static approach.

A radical novelty of this scheme is the fact that it is proactive, based on prediction rather than pure feedback-based reactive. The choice of the utility function should depend on the needs of the individual problem and this flexibility is an additional virtue of the technique.

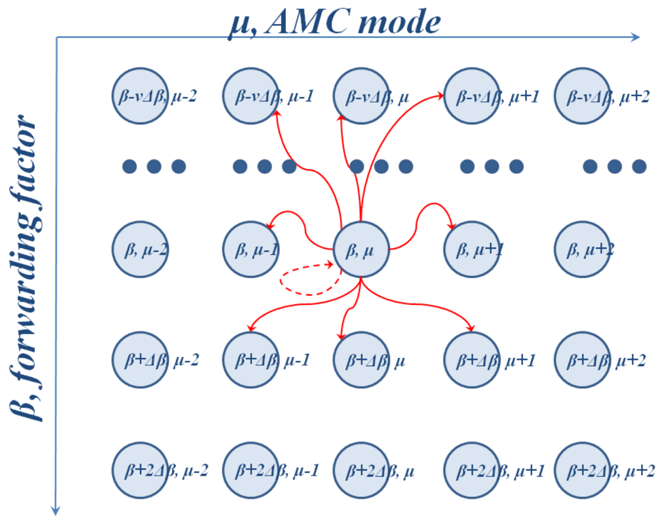

Fig. 1. Markov finite state machine describing the state transitions of a node.

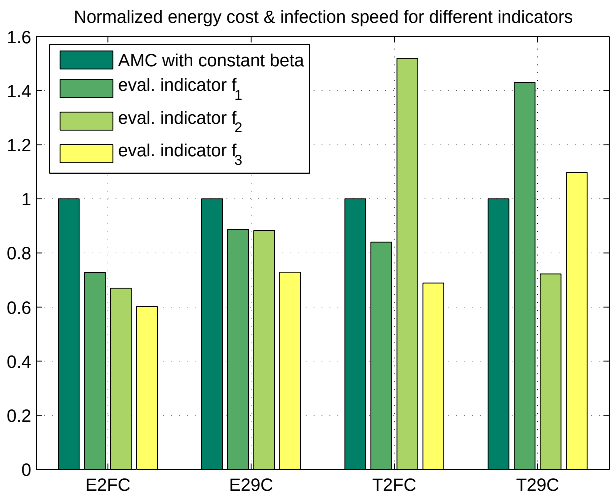

Fig. 2. Performance of a simple benefit prediction-based AED scheme.

2.3 Epidemic Dissemination with Optimization

The aforementioned technique may be further improved through an additional modification: *The most beneficial of the actions in Table 1 is actually adopted if and only if an optimal stopping (OS) condition is also simultaneously satisfied.*

Thus, OS is introduced as an additional term and the examined problem is addressed as an OS problem with infinite time horizon. The *one-stage-look-ahead* (1sla) rule has been chosen as the OS condition here to serve in a proof-of-concept setting. This is, however, optimal in problems with infinite temporal horizon only if the problem is monotonous with the specific utility function. With some assumptions it may be shown that the monotonicity condition is satisfied with a finite probability.

This "conservative" approach in tuning the transmission characteristics also delivers energy cost reduction with hardly any compromise in the epidemic infection.

2.4 Optimized Scheduling with Plesioperiodic Broadcasts

The acquired knowledge may be exploited for addressing transmission scheduling problems.

Many processes in modern wireless networks utilize temporal broadcasts for information dissemination. Examples are schemes like *directed diffusion* and some routing protocols such as AODV, DSR, LOADng, etc

Let us consider such a system in which the infected nodes periodically broadcast the information they possess -which is effectively the *infecting information*. Let the transmission period be ϵ. The following model is proposed instead of periodic broadcasts:

The temporal field is distributed in consecutive, non-overlapping time intervals of duration ϵ, which are termed *epochs*. Within each epoch the infected node solves the *classical secretary problem* with finite temporal horizon.

It starts from state (β, μ). At every time instance it evaluates the promised immediate benefit of the most beneficial of the actions of Table 1. When the OS condition is satisfied, as known from the secretary problem, this action is adopted and the node state is modified. Epidemic transmission takes place from this state and the node remains silent for the remainder of the current epoch.

Hence, a scheme of repeated epidemic broadcasts is adopted, which are performed within defined time limits but without the interval between two consecutive ones being constant.

In this manner, addressing the information dissemination problem transits from periodic to near-periodic or *plesioperiodic* as depicted in Figure 3.

The implementation of such a scheme assumes knowledge of the count of immediate neighboring nodes and the channel state information (CSI). This kind of context awareness is a quite common assumption in AED. Its advantages include the flexibility in choosing a utility function and also the energy cost reduction down to levels comparable with fully passive methods.

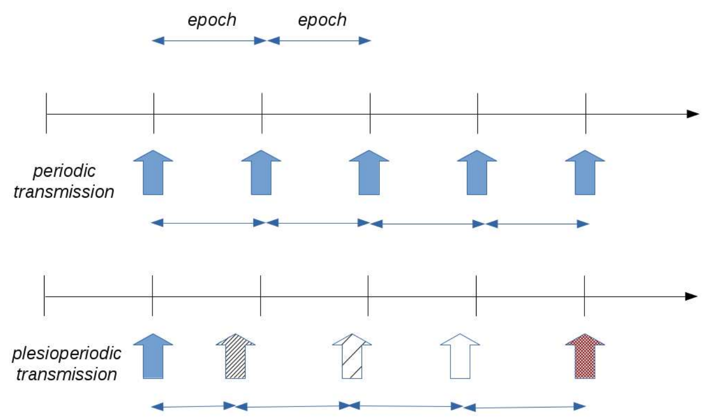

Fig. 3. Transition from strict periodicity to near-periodicity or *plesioperiodicity.*

The fields of application of such an improved scheduling method would include *route request* (RREQ) message dissemination in routing protocols. This constitutes an attempt to improve the performance of the dissemination of such messages using the described plesioperiodic approach.

Energy cost reduction compared to the unconditional message dissemination is expected. However, it is useful that other factors are taken into account. In the routing problem, a most interesting problem is that of encountering a node with the desired routing information. The latter is derived from the extent that the "epidemic", i.e. the information dissemination, finally assumes. Hence, the need for a tradeoff arises between energy cost save and routing information discovery.

Scheduling the infecting information transmissions is formulated as follows:

- At every time instance $t \in \mathbb{N}$ the state of an infected node is described by the pair $h = (\beta, \mu) \in B \times M$, where B and M the sets of possible values of β and μ respectively.
- The state may change through the adoption of an action α from a finite set of possible actions $\mathcal{A}$, such that $(\beta, \mu) \xrightarrow{\alpha \in \mathcal{A}} (\beta', \mu')$. It always holds that $(\beta, \mu) \in B \times M$ and $(\beta', \mu') \in B \times M$. That is the set $B \times M$ is closed under every action $\alpha \in \mathcal{A}$.
- Considering the time field divided up into *epochs*, the action α is adopted at time t_{ost}, that is one time *at maximum* within the current epoch. For the n-th ($n \in \mathbb{N}$) epoch of duration ϵ, same as the aforementioned period, this can be written as $t_{ost} \in E_n = \{n\epsilon, n\epsilon + 1, ..., (n+1)\epsilon - 1\}$, as we are dealing with a discretized time field. Therefore, in each epoch, that is $\forall n \in \mathbb{N}$, the optimal instance for state transition and broadcast from that new state is sought.
- Possible actions are evaluated using a utility function U. This is calculated $\forall t \in \mathbb{N}$, hence also for $\forall t \in E_n$.

For each epoch, i.e. $\forall n \in \mathbb{N}$, the pair $(\alpha, t_{ost}) \in \mathcal{A} \times E_n$ is termed the *optimal policy* for this epoch. That is:

The optimal policy is the decision as to which is the optimal moment within the epoch for the optimal action to be performed, which changes the node state.

As we saw, the node broadcasts from this new state. Therefore the problem is written formally as:

$$\boxed{\forall n \in \mathbb{N}, \text{ policy sought } (\alpha^*, t^*_{ost}) \in \mathcal{A} \times E_n : (\alpha^*, t^*_{ost}) = argmax_{(\alpha, t_{ost})} U_n(\alpha, t_{ost})}$$

The performance of the proposed technique is evaluated in an environment with mobile nodes where collisions in wireless channels and the CSI-acquisition energy cost are also considered. In figure 4 it is displayed in comparison to other adaptive and non-adaptive ones. It emerges as efficient as a fully passive benchmark and it also becomes apparent that a significant part of its residual energy cost is attributable to the context acquisition.

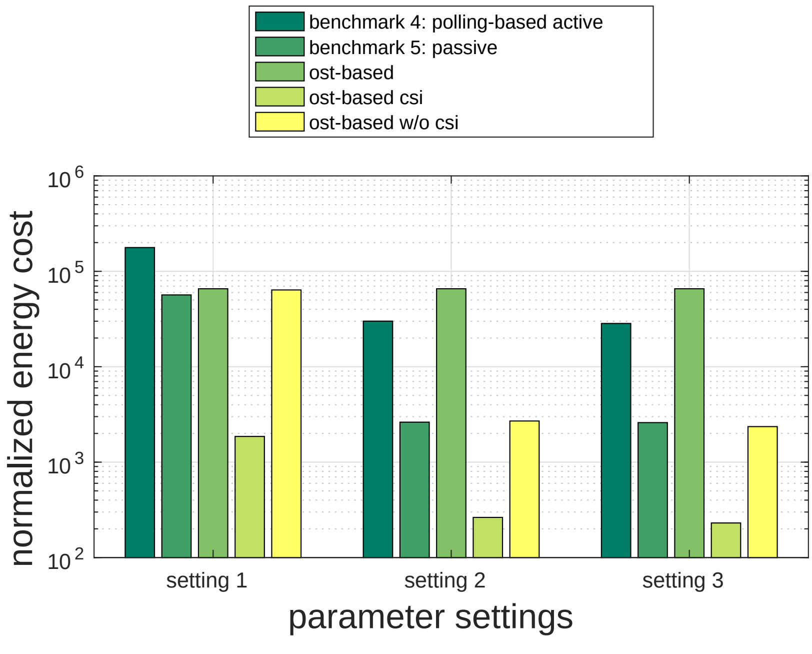

Fig. 4. Performance of an OS-based AED scheme. The discrete bundles of bars correspond to various problem parameter settings.

2.5 Applications in routing

Following the newly introduced formulation, the scheduling problem can be addressed under various conditions and requirements. In any case, of course, a suitable utility function is required for the evaluation of the benefit evaluation.

Context awareness can be broadened to include network density ρ changes for the decisions to increase or decrease β and μ. Table 1 then transits to Table 3. This, of course, is senseful mostly in a setting with mobile nodes.

Table 3. Context awareness in deciding to increment or decrement β and μ.

context information	SNR increase	SNR decrease
increment ρ	decrement β, increment μ	increment β, decrement μ
decrement ρ	decrement β, increment μ	increment β, decrement μ

Such a scheme can be utilized in the route request message (RREQ) broadcast scheduling problem.

An interesting aspect is the comparison of the behavior between random and scale-free networks. It is observable that in scale-free networks the same encouraging performance is observable. Naturally, the study of this type of networks is a whole new area by itself.

Context awareness can be further broadened through the inclusion of elements from the carried information itself (payload). Then the adaptation of the infected nodes state that was described earlier obtains a more information-centric character. For example, an application in the AODV routing protocol is amplifying the forwarding probability of a message when that is characterized by a still high TTL (time-to-live) value. In this manner, the disseminated information retains a young age.

The need for a tradeoff among three requirements arises:

- Energy cost reduction
- Broad information dissemination
- Retention or improvement of information quality

The techniques described have cross-layering in common. This property appears in our research in two aspects as both the context information and the adapted parameters are from various layers:

- The context information includes some of the following parameters: count of immediate neighbors, CSI between each node and its neighbors, proportion of malformed messages, number of duplicates and TTL. These are mostly associated with the physical layer and possibly the higher (application) layer.
- Adapted parameters include the forwarding probability and the AMC mode, hence the lower and network layers are involved.

3 Conclusions

Optimizing AED in demanding ad hoc network environments is an exciting problem. Exploiting the cross-layer nature of AED allows for pursuing a beneficial tradeoff among a number of competing requirements which may depend on the specific problem.

In this thesis we present a framework for flexible AED schemes that contributes in this direction as follows:

- Reaching optimal tradefoff among competing requirements
- Allowing for the inclusion of requirements associated with various layers depending on the specific problem and setting
- Addressing the transmission scheduling problem with the transition from periodicity to *plesioperiodicity*
- Showing that ad hoc network routing is a primary field of application for such schemes

In the schemes presented in this thesis broad infection of the network with information is achieved while the energy cost is significantly reduced. Retention or improvement of information quality is also investigated. Routing in ad hoc networks is shown to be a primary application field.

This approach achieves broad spread of high quality information while prolonging the network lifetime.

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