Study of the group-based approach to disseminate control information in wireless network

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Abstract

Various networking protocols disseminate much control information. An important task is to reduce the amount of such information in order to free channel resources for user data. In the paper, we study a novel group-based approach for dissemination of control information introduced in the latest version of the IEEE 802.11 standard. The key idea of this approach is to join various pieces of information into a small number of groups and send differential updates related only to those groups which content is changed. However, the group management algorithm (GMA) which directly affects the performance of such an approach is not specified. We consider a simple GMA, develop an analytical model to estimate the amount of sent control information, and show that this amount is significantly less than for the classical full dump approach.

I. INTRODUCTION

Many protocols currently used in wireless networks generate and disseminate much control information. For example, routing protocols disseminate information about links and their quality, channel access protocols disseminate scheduling information, multicast group management protocols disseminate information about group membership, and so on.

The simplest approach to disseminate control information (also called *full dump* or *full advertisement*) is to periodically send messages containing all information even if it is not changed. In particular, such an approach is used in well-known proactive routing protocol OLSR [1], in which each station (STA) periodically broadcasts information about all links established with its neighbors. Apparently, this approach leads to huge overhead because STAs send redundant information when nothing is changed. Since for transmission of both control information and user data, STAs typically use the same channel, we need to reduce the amount of sent control information, but, at the same time, to provide STAs with up-to-date information [2].

A more intelligent approach to disseminate control information is to send incremental messages (differential updates) containing only changes of the information. In particular, such an approach is used in routing protocols TBRPF [3] and OSPF-MDR [4]. The benefit of interleaving full messages with incremental ones is widely studied in literature, e.g., see [5], [6]. To refer to a particular piece of information included in an incremental message, each STA shall label various pieces of information with unique identifiers (IDs). However, when the total number of pieces of information is large, the length of ID becomes high. This eventually leads to additional overhead. One of the ways to address this problem is to join different pieces of information into a relatively small number of groups. When the content of a group is changed, the STA sends an incremental message only about the changes in this group. In particular, such an approach (which we call *group-based*) is employed in the latest version of the IEEE 802.11 standard [7].

This version introduces a novel channel access protocol called Mesh coordination function Controlled Channel Access (MCCA), which allows STAs of a wireless multihop network to reserve periodic time intervals for data transmission. MCCA is a distributed protocol, which means that each pair of STAs negotiates their reservation with their neighbors (the reader can refer to [8], [9] for detailed description of MCCA). To prevent other STAs from transmission in the reserved time intervals, each STA periodically broadcasts information about reservations already established by this STA and by its neighbors. This procedure is called reservation advertisement and is described in detail below.

According to the standard, to reduce the amount of advertised information, a STA divides all reservations it is aware of into several groups. The total number of groups is limited by parameter G (in IEEE 802.11, $G = 16$). Each STA periodically broadcasts a special management frame called beacon. To notify neighboring STAs about non-empty groups, the STA includes a short message called Advertisement Overview in every beacon. This message contains the following fields:

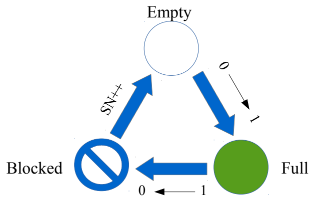

Fig. 1. Group life cycle

- G-bit bitmap in which bit i equals 0 if group i is empty, and equals 1 otherwise;
- sequence number (SN) which identifies the actual version of the bitmap.

Information about reservations included in a group (the content of the group) is sent only on the group creation, i.e., when the corresponding bit is changed from 0 to 1. With the same SN, the content of the group cannot be modified. However, the group can be removed as a whole. In particular, if a reservation is deleted from a group, the whole group shall be removed (the corresponding bit changes from 1 to 0), while the remaining reservations shall be moved to one or more empty groups. The bits are not reusable: a new group cannot correspond to a bit previously used for another group with the same SN. In other words, with the same SN, each bit can be changed from 0 to 1 and then from 1 to 0 only once. This restriction is introduced because in wireless networks several Advertisement Overview messages may be lost, e.g., due to erroneous transmission. Multiple changes of the same bit with the same SN may lead to the ambiguity problem. If a STA needs to create a new group, but no bit remains free, the SN is increased, and all the reservations are divided into groups from scratch. Only in this case, the STA sends information about all the reservations, since all groups are new.

Neighboring STAs process messages describing reservations as follows. Having received an Advertisement Overview message, a STA compares the SN value and the bitmap with the previously received ones. If only the bitmap is changed, the STA (i) removes information about reservations of deleted groups (for which the corresponding bits have changed from 1 to 0) and (ii) adds information about reservations of new groups (for which the corresponding bits have changed from 0 to 1). If SN is changed, the STA (i) removes information about all the reservations previously received from the neighbor and (ii) adds information about reservations of all non-empty groups indicated in the bitmap since all such groups are new. If the STA has not received information about reservations of some new group yet, it can request this information from the neighbor by sending a special management frame.

Note that with the described above group-based approach, the amount of advertised information significantly depends on how STAs group reservations. However, the standard does not specify any group management algorithm (GMA). Besides that, we have not found any papers studying GMA. Our paper is the first step to fill this research gap. In Section II, we consider a simple GMA which is based on the idea to minimize the frequency of SN changes. In Section III, we develop an analytical model to analyze the efficiency of group-based approach combined with the proposed GMA and to compare it with the *full advertisement approach* (i.e., when a STA periodically advertises all reservations). Using the model, in Section IV, we show that even with a simple GMA the group-based approach allows more than two times reducing the amount of advertised information in comparison to the full advertisement approach. Besides that, we describe and numerically evaluate a modification of the proposed GMA which provides even better results. In Section V, we conclude the paper and discuss directions of further research.

II. GROUP MANAGEMENT ALGORITHM

To describe the proposed GMA let us introduce some notations. Reservations are divided into G groups, which are enumerated from 1 to G. With a given SN, each group can be in one of the following states:

- *Empty (E)*. The group has not contained reservations under this SN yet. The corresponding bit equals 0.
- *Full (F)*. The group contains at least one reservation, and the corresponding bit equals 1.
- *Blocked (B)*. The group does not contain reservations (the corresponding bit equals 0), but under the same SN it previously contained reservations. Thus no reservations can be put in this group until SN changes.

Fig. 1 shows the life cycle of each group. Consider a group in state F. If one or several reservations in this group are closed, the group changes its state to B and all the remaining reservations are moved to one or several empty groups. The corresponding bit in the bitmap changes from 1 to 0. After that, the group may change its state only when SN increases.

As mentioned in Section I, when SN changes, information about all the reservations is sent. We propose a simple GMA, which is based on the idea to put reservations in as few groups as possible, so that SN changes more rarely. Formally, the algorithm works as follows. We assume that the advertisement information is broadcast periodically in beacons, and reservations are arranged into groups right before a beacon transmission. Suppose that during the considered beacon interval, n new reservations are established and d existing reservations are closed. The following cases are possible:

1) $n = 0, d = 0$. In this case, the groups do not change, and, hence, SN and the bitmap do not change too.

2) $n = 0, d > 0$. The algorithm performs the following steps.
    a) The groups, in which one or more reservations are closed, change their states to B.
    b) Remaining reservations in the blocked groups should be rearranged as follows.
        i) If there is at least one group in state E, then all reservations remaining from the blocked groups are put into this group.
        ii) If there are no groups in state E, SN is increased by 1. All the reservations, which STA is aware of, are put into the first group.
3) $n > 0, d = 0$. Two cases are possible.
    a) If there is a group in state E, then all new reservations are put into it.
    b) If there are no groups in state E, then actions described in the item 2bii) are performed.
4) $n > 0, d > 0$. The actions described in items 2) and 3) are consequently performed. All the reservations from the blocked groups and new ones established in the current beacon interval are put into the same group.

III. ANALYTICAL MODEL

Let us evaluate performance of the proposed GMA. As mentioned in Section I, a STA tracks and advertises all reservations established by this STA and its neighbors. The STAs establish reservations when new data flows arrive and close them when the corresponding data flows are finished. Let the total number of data flows arriving at the considered STA and its neighbors in a beacon interval have the Poisson distribution with mean value λ. The lifetime of each data flow and the corresponding reservation has exponential distribution with rate parameter μ. We assume that all new reservations are established at the end of the beacon interval and therefore the lifetime starts to count down at the beginning of the following beacon interval. Since the standard limits the number of reservations that each STA can track, we introduce threshold R. If the number of tracked reservations reaches R, no more reservations can be established, and thus any arriving data flow is discarded. We also assume that beacons carrying information about reservations are delivered to all neighboring STAs reliably, so it is not retransmitted.

Let us estimate the reduction of advertised information achieved by the proposed GMA in comparison to the full advertisement approach. In this paper, we estimate the amount of advertised information as the number of reservations, information about which is put into the beacon. As the size of an Advertisement Overview message (SN and bitmap) is smaller than the size of a message describing one reservation, we neglect regular transmissions of the Advertisement Overview messages.

A. *Full advertisement*

We introduce a discrete-time Markov chain. Consider a single STA, which state is described by number r of reservations. We observe its state at the discrete time moments, which correspond to the beginnings of beacon intervals. Let us find transition probabilities $p_{r'|r}$.

Assume that during the considered beacon interval, f new data flows arrive and d reservations are closed. Then, at the end of the beacon interval, the number of reservations becomes equal to $r' = \min(r - d + f, R)$. In our scenario, f has probability distribution function $p_f(f) = \frac{\lambda^f}{f!}e^{-\lambda}$, $f = 0, 1, ...\infty$. Since the lifetime of each reservation has exponential distribution, the probability of closing a particular reservation during the beacon interval equals $\tilde{p} = 1 - e^{-\mu}$ and does not depend on the time during which reservation already exists. As lifetimes of different reservations are mutually independent random variables, then the probability of closing d reservations from r reservations equals $p_{d|r}(d|r) = C_r^d \tilde{p}^d (1 - \tilde{p})^{r-d}$, $0 \leq d \leq r$.

As the total number of reservations shall not exceed R, for f new data flows only n ($n \leq f$) new reservations can be established. With given d and r, $n \leq R + d - r$. Consider two cases.

1) If $n < R + d - r$, then reservations are established for all the incoming data flows, so $f = n$. In this case, the probability of establishing n reservations equals $p_f(n)$.
2) If $n = R + d - r$, then f can be any from n to ∞ because the STA cannot track more than R reservations. Hence, the probability of establishing n reservations equals

$$\sum_{f=n}^{\infty} p_f(f) = \begin{cases} 1 - \sum\limits_{f=0}^{n-1} p_f(f), & n > 0, \\ 1, & n = 0. \end{cases}$$

Combining two cases, the conditional probability of establishing n new reservations at given r and d values equals:

$$p_{n|r,d}(n|r,d) = \begin{cases} p_f(n), & n < R + d - r, \\ 1 - \sum\limits_{f=0}^{n-1} p_f(f), & 0 < n = R + d - r, \\ 1, & 0 = n = R + d - r. \end{cases}$$

Now let us find transition probabilities $p_{r'|r}$. If there are r reservations at the beginning of the beacon interval, d reservations are closed during the beacon interval and the number of reservations changes to the value r', then $n = r' - r + d$ reservations are established. Since $n \geq 0$, $d \geq r - r'$. Summing over all possible values of d, we get:

$$p_{r'|r} = \sum_{d=\max(0,r-r')}^{r} p_{d|r}(d|r)p_{n|r,d}(r' + d - r|r, d)$$

Using the found transition probabilities, we can find stationary probabilities π_r. Since for the full advertisement approach, information about all reservations is sent every beacon interval, the mean amount of advertised information can be estimated as follows:

$$\mathrm{E}[V_{full}] = \sum_{r=0}^{R} \pi_r r.$$

B. Group-based advertisement

Now we estimate the mean amount of advertised information for the GMA described in Section II. For that, we describe the algorithm operation with two variables:

1) g is the number of groups in state E, $g = 0, 1, ..., G - 1$;
2) r is the total number of reservations, $r = 0, 1, ..., R$.

Note that number r of reservations does not depend on the used advertisement approach, so it does not depend on number g of empty groups. So, we can consider the evolution process of r and g separately. However, the amount of advertised information depends on both r and g.

According to the proposed algorithm, every beacon interval, g remains unchanged or decreases by 1 modulo G. Thus, let us introduce function $f(g) = (g-1) \mod G$. Fig. 2 shows all the transitions from state (g,r). A special attention should be drawn to transition 3, which corresponds to the case when all the reservations from one or more groups are closed and no reservation is established. The groups left without reservations become blocked, while the others do not change their state. So, g remains unchanged.

Let us estimate the amount of advertised information in each transition. In transitions 1, 2, and 3, the STA does not send any information about reservations. In other transitions, the amount of advertised information depends on the number of reservations in each group, which is unknown in our model. However, we can estimate the upper bound of the mean amount of advertised information using the following assumption.

Note that the amount of advertised information is maximal if all the reservations are arranged in one group. Indeed, if at least one reservation is closed in this group, the STA sends information about all the reservations. So, in transitions 5 and 6 information about all r' reservations is sent. As for transition 4, if $d = 0$, information only about reservations established in the current beacon interval is sent, otherwise information about all the reservations is sent. According to the introduced assumption, transition 3 does not occur.

Let us divide the algorithm operation into two phases: $g > 0$ and $g = 0$. The mathematical expectation of amount V_{gb} of advertised information can be calculated from the conditional mathematical expectations for each phase as follows:

$$\begin{aligned}\mathrm{E}[V_{gb}] = \mathrm{E}[V_{gb}|g > 0]\Pr(g > 0) + \\ +\mathrm{E}[V_{gb}|g = 0]\Pr(g = 0).\end{aligned} \tag{1}$$

Let us find the conditional mathematical expectations $\mathrm{E}[V_{gb}|g = 0, r]$ and $\mathrm{E}[V_{gb}|g > 0, r]$ in each phase when the total number of reservations equals r. Consider all the transitions from the current state to the state with r' reservations. For convenience, we introduce function $\hat{p}(d|r, r')$ which is the probability that d reservations are closed, given r and r': $\hat{p}(d|r, r') = p_{d|r}(d|r)p_{n|r,d}(r' - r + d|r, d)$.

First, consider $g = 0$. In transition 1, the STA does not send any information about reservations. The probability of this transition equals $\hat{p}(0|r, r)$. In transition 2, the STA does not send information about reservations since $r' = 0$. In transitions 4, 5 and 6, it advertises all r' reservations since SN increases. So, the conditional mathematical expectation equals:

$$\mathrm{E}[V_{gb}|g = 0, r] = \sum_{r' \neq r} p_{r'|r}r' + (p_{r|r} - \hat{p}(0|r, r))r. \tag{2}$$

Now consider the case when $g > 0$. If in transition 4 $d = 0$, then $r' - r$ new reservations are established and STA sends information only about them. The probability of this transition equals $\hat{p}(0|r, r')$. In other transitions, the amount of advertised

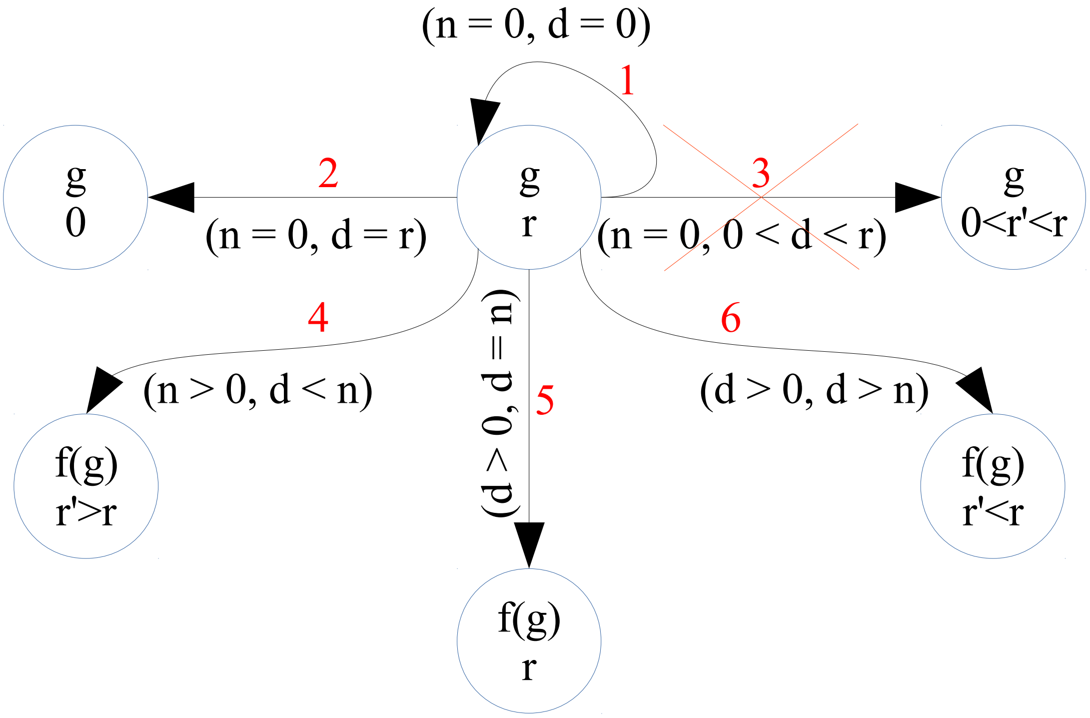

Fig. 2. Transitions from the state with r reservations and g empty groups

information is the same as in case $g = 0$. Then, the conditional mathematical expectation equals:

$$\mathrm{E}[V_{gb}|g>0,r] = \sum_{r'<r} p_{r'|r} r' +$$
$$+ \sum_{r'=r}^{R} (\hat{p}(0|r,r')(r'-r) + (p_{r'|r} - \hat{p}(0|r,r'))r'). \tag{3}$$

Variables r and g are independent, so conditional stationary probabilities $\pi_{r|g}$ are equal to stationary probabilities π_r found in Section III-A. So, for any g value we can find:

$$\mathrm{E}[V_{gb}|g] = \sum_{r=0}^{R} \mathrm{E}[V_{gb}|g,r] \cdot \pi_r. \tag{4}$$

Let us find probabilities $\Pr(g=0)$ and $\Pr(g>0)$. Consider a one-dimensional Markov chain of the g change process. At the beginning of every beacon interval, g remains unchanged in two cases: (i) $n = 0, d = 0$; (ii) $n = 0, d = r$, and probabilities of the cases are $\hat{p}(0|r,r)$ and $\hat{p}(r|r,0)$, respectively. In all other cases, g decreases by 1 modulo G. Summing over all possible r values, we can calculate transition probabilities $\Pr(g|g) = \sum_{r=0}^{R} (\hat{p}(0|r,r) + \hat{p}(r|r,0)) \cdot \pi_r$ and $\Pr(f(g)|g) = 1 - \Pr(g|g)$. We can see that these probabilities do not depend on g, thus the stationary probabilities $\Pr(g=0)$, $\Pr(g=1)$, ..., $\Pr(g=G-1)$ are equal to each other. Hence, $\Pr(g=0) = \frac{1}{G}$ and $\Pr(g>0) = \frac{G-1}{G}$.

By substituting the found probabilities into (1), we obtain:
$\mathrm{E}[V_{gb}] = \frac{1}{G} \cdot \mathrm{E}[V_{gb}|g=0] + \frac{G-1}{G} \cdot \mathrm{E}[V_{gb}|g>0]$,
where conditional mathematical expectations are estimated, based on (2), (3) and (4).

IV. NUMERICAL RESULTS

In this Section, we evaluate the efficiency of the group-based approach with the proposed GMA and compare it with the full advertisement approach. In the experiments below, we set $R = 100, G = 16$.

Fig. 3 shows the dependencies of the mean amount of advertised information from parameter $\rho = \lambda/\mu$ at different μ values, obtained analytically and by simulation. Simulation results are obtained for the proposed GMA without applying the assumption that all reservations are arranged in the same group. We can see that the usage of the full advertisement approach leads to extremely high amount of advertised information, which almost does not depend on μ value (the lines corresponding to different μ values are close to each other). When μ is low (i.e., when the average lifetime of a reservation is high), the proposed GMA significantly decreases the amount of advertised information. In particular, when $\mu \sim 0.01$, the amount of advertised information is halved. However, when μ increases, the amount of advertised information increases too, and, when $\mu = 0.1$, it is almost the same as for the full advertisement approach. Such a behaviour can be explained by the fact that with increasing μ, the average reservation lifetime decreases, and thus, reservations are closed more often. According to our GMA, reservations tend to be arranged into one group with time. So, after at least one reservation is closed, the STA sends information about all the reservations, similar to the full advertisement approach.

To avoid this drawback, let us consider the following modification of the GMA. When SN increases, all the reservations are arranged not in the same group as described in Section II (item 2bii), but in the first K groups ($K \leq G$). Fig. 4 shows simulation results for different K and μ values. We can see that by a proper choice of K the amount of advertised information can be significantly reduced. When K increases from 1 up to some optimal value, the amount of advertised information decreases. Indeed, when reservations are divided into several groups, the advertisement of all reservations occurs only when at least one reservation is closed in each group, and the probability of such event decreases with K. However, when K grows further, the amount of advertised information starts to grow because with increasing K, the number of empty groups decreases, and thus

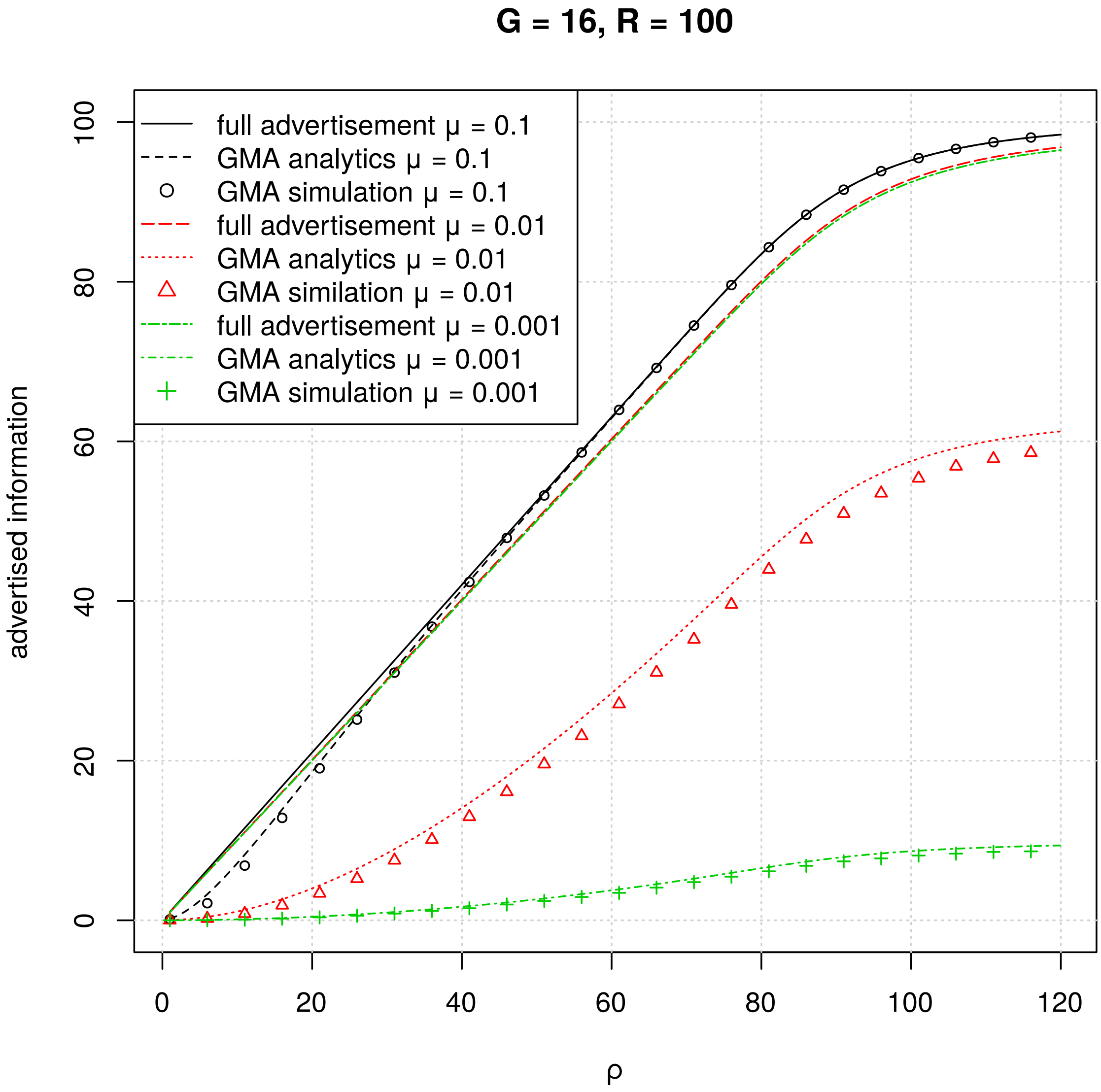

Fig. 3. Comparison of the proposed GMA with the full advertisement approach for different μ values.

SN increases more frequently. We can see that optimal K value significantly depends on μ. Our future plans are to analytical study the modified GMA and to develop a method for determining optimal K value.

V. CONCLUSION

In this paper, we have studied a novel group-based approach for control information dissemination, proposed in the latest version of IEEE 802.11 standard. Its key component is the group management algorithm (GMA). We have proposed a simple GMA and developed an analytical model, which allows to estimate the mean amount of sent control information. The numerical results have shown that even with the simple GMA the group-based approach allows to significantly reduce the amount of sent control information, comparing with the classical full advertisement approach. Also we have proposed and numerically studied a modification of GMA, which provides even better results. We believe that combined with an intelligent GMA the group-based approach can provide benefits not only for MCCA, but for other protocols which require dissemination of control information, e.g., routing protocols, multicast group management protocols, and others. Our future plans are to analytically study the modified GMA and to propose a method for its self-tuning. In addition, we are going to carry out a comparative analysis of different GMAs to find the best one.

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REFERENCES

[1] T. Clausen, P. Jacquet, Optimized Link State Routing Protocol (OLSR), RFC 3626 (Oct. 2003).

[2] A. Lyakhov, P. Nekrasov, D. Ostrovsky, A. Safonov, E. Khorov, Analysis of the joint use of the proactive and reactive methods of the topology information dissemination in ad-hoc wireless networks, Journal of Communications Technology and Electronics 57 (12) (2012) 1322–1330.

[3] R. Ogier, F. Templin, M. Lewis, Topology Dissemination Based on Reverse-Path Forwarding (TBRPF), RFC 3684 (Feb. 2004).

[4] R. Ogier, P. Spagnolo, Mobile Ad Hoc Network (MANET) Extension of OSPF Using Connected Dominating Set (CDS) Flooding, RFC 5614 (Aug. 2009).

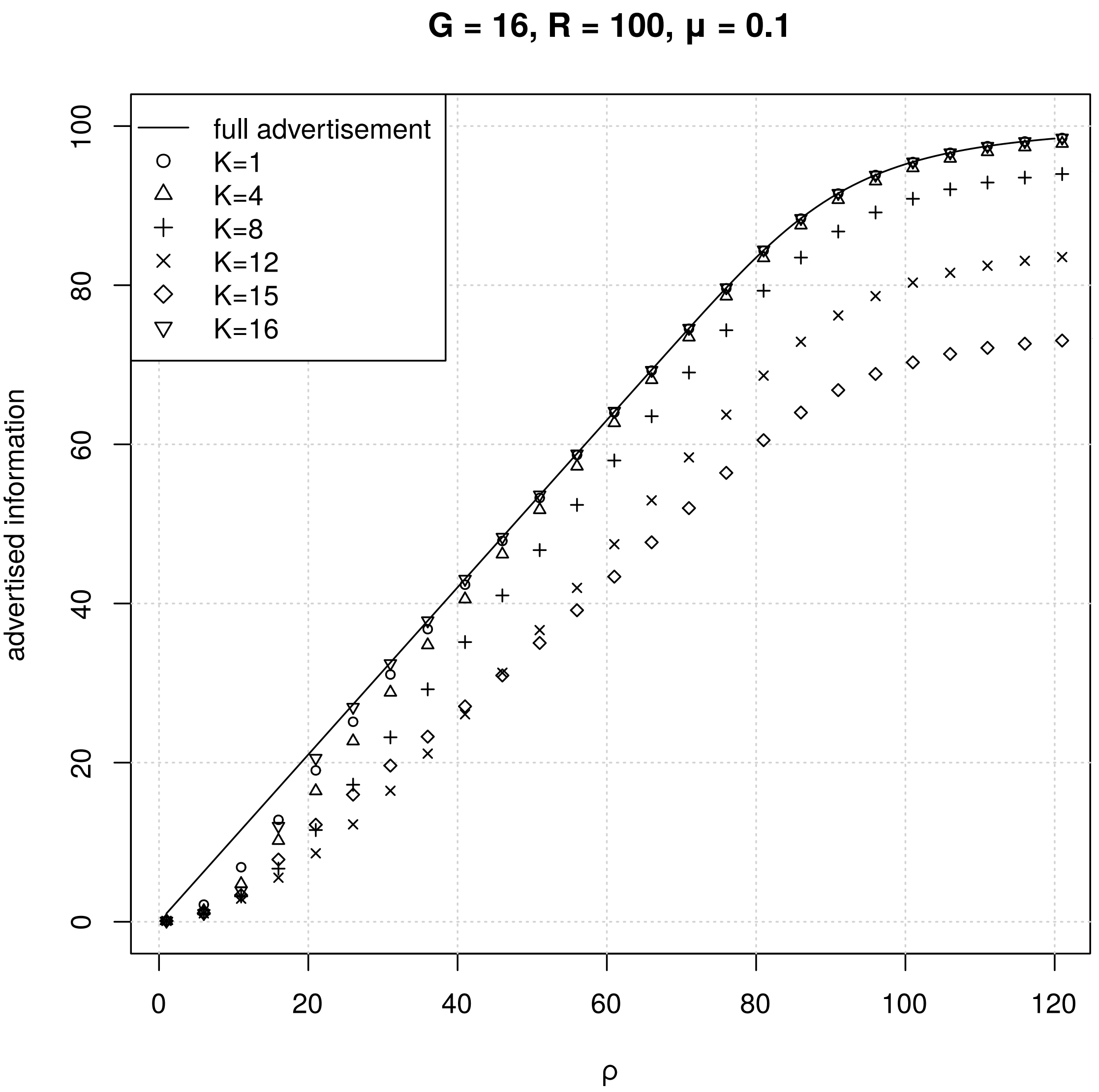
[5] B. Bellur, R. Ogier, A reliable, efficient topology broadcast protocol for dynamic networks, in: Proc. INFOCOM '99, IEEE, 1999, pp. 178–186.

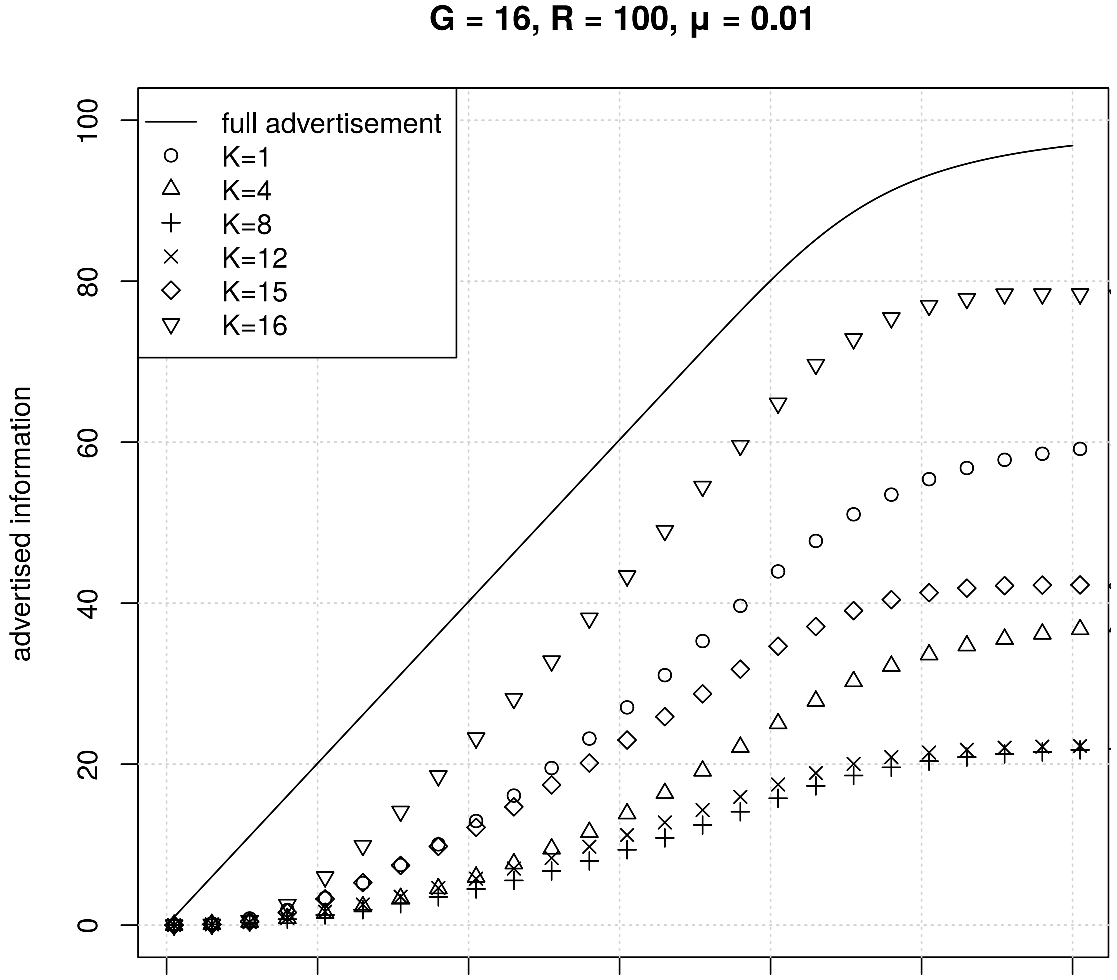
[6] Z. Wang, Y. Chen, C. Li, A new loop-free proactive source routing scheme for opportunistic data forwarding in wireless networks, IEEE Communications Letters 15 (11) (2011) 1184–1186.

[7] 802.11-2012 - IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.

[8] A. Krasilov, A. Lyakhov, A. Safonov, Interference, even with MCCA channel access method in IEEE 802.11s mesh networks, in: Proc IEEE MASS'2011, pp. 752–757.

[9] A. Ivanov, A. Lyakhov, E. Khorov, Analytical Model of Batch Flow Multihop Transmission in Wireless Networks with Channel Reservations, Automation and Remote Control 76 (7).


G = 16, R = 100, μ = 0.1
full advertisement
K=1
K=4
K=8
K=12
K=15
K=16
advertised information
0
20
40
60
80
100
0
20
40
60
80
100
120
ρ


G = 16, R = 100, μ = 0.01
full advertisement
K=1
K=4
K=8
K=12
K=15
K=16
advertised information
0
20
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80
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